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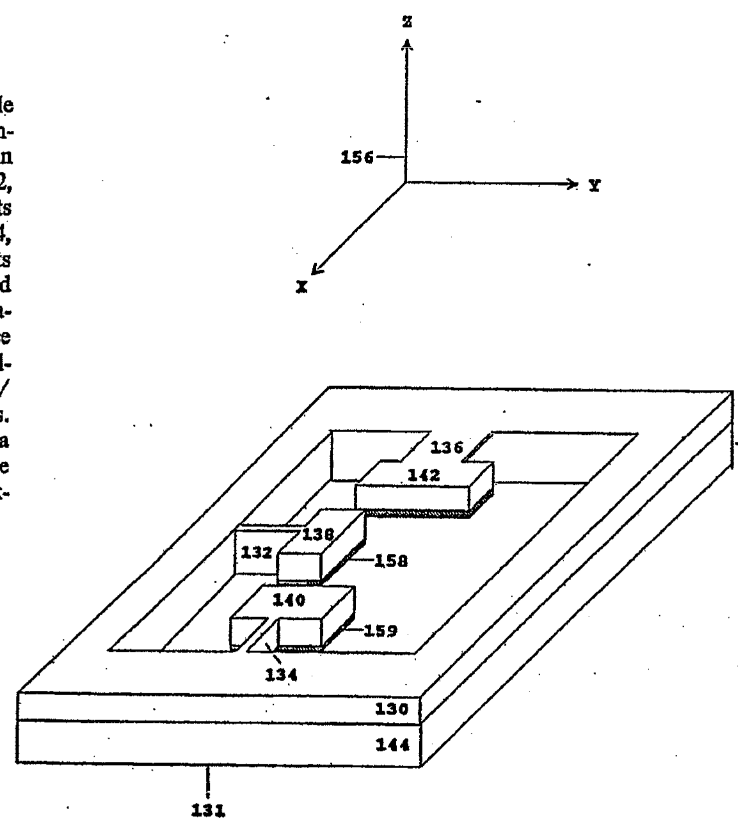
(54) Title: MULTIDIMENSIONAL FORCE SENSOR

(57) Abstract

This invention relates to sensors capable of sensing multiple dimensions of force. One embodiemnt of this invention comprises a main body (130) having multiple flexible beams (132, 134, 136) with one or more response elements (138, 140, 142) attached to the beams (132, 134, 136). Displacement of the response elements (138, 140, 142) caused by a force may be detected with a variety of sensing methods, including capacitive and piezoresistive sensing. The force may arise from linear acceleration, angular acceleration, angular velocity, fluid flow, electric/magnetic/gravitational fields, and other sources. This sensor may be used as an accelerometer or a field sensor in environments in which multiple dimensions of acceleration or force may be expected.



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DESCRIPTION

MULTIDIMENSIONAL FORCE SENSOR

Technical Field

The present invention generally relates to accelerometers and force sensors, and particularly those capable of sensing multiple dimensions of force. Of particular interest are forces arising from linear acceleration, angular velocity (centrifugal force), angular acceleration, gravitational fields, electric fields, magnetic fields, viscous drag, and other frictional drag forces.

The parent U.S. application, Serial No. 07/220,073, filed July 14, 1988, which application (including all appendices) is hereby incorporated herein by reference, contains a computer program listing, various mathematical analyses, technical information on fabrication of some preferred embodiments of the invention, and discussion of device calibration and design considerations.

Background Art

Devices which are currently used to measure force include accelerometers utilizing capacitive, piezoelectric, and piezoresistive silicon structures. Such devices usually measure only a force magnitude, or perhaps only one single force component of a multiple component force vector. Such devices commonly use capacitive sensing or piezoresistive sensing.

An example of a device employing capacitive sensing is described in Rudolf, U.S. Patent No. 4,483,194 (incorporated herein by reference), which describes a hinged cantilever structure which uses capacitance sensing for an accelerometer sensitive to a single dimension.

The article "A Batch-Fabricated Silicon Accelerometer" (L.M. Roylance and J.B. Angell), which appeared in IEEE Trans. on Electron Devices, Volume ED-26, No. 12, December 1979, pp. 1911 - 1917 (incorporated herein by reference), describes a single cantilever beam

etched from a single crystalline silicon with a diffused resistor acting as the strain sensing element.

Walker, U.S. Patent No. 4,315,693 (incorporated herein by reference), describes an optical sensing method for measuring angular acceleration using a passive ring Fabry-Perot interferometer.

Sulouff et al., U.S. Pat. No. 4,522,072 (incorporated herein by reference) describes a single mass loaded cantilever beam and claims "dual axis acceleration measurement."

Colton, U.S. Pat. No. 4,430,895 (incorporated herein by reference) describes a central pedestal surrounded by a strain sensing membrane and states sensitivity to one and three components of linear acceleration.

Accelerometers having multiple axes of sensitivity have been achieved by combining multiple single axis resolving devices along more than one axis within a single hybrid accelerometer package. However, this approach tends to increase the size of the accelerometer. Related assembly also can be costly. Further, single axis resolving devices may be prone to errors from off-axis acceleration components. Therefore, a single integral sensor capable of measuring multiple independent force components would provide advantages in cost reduction, size, design options and performance.

Piezoresistive sensing methods are highly temperature dependent and are also dependent on doping and orientation factors. Capacitive sensing methods provide attractive alternatives because they are relatively insensitive to temperature, are not doping dependent, and are easily fabricated. Thus, a multidimensional sensor utilizing capacitive sensing methods would be very attractive.

<u>Disclosure of Invention</u>

The invention is a multidimensional force sensor comprising a main body, a plurality of beams attached to the main body, and methods for sensing displacement of the beams in response to force. The invention includes

the use of novel capacitor groupings and capacitor plate geometries. Response elements are attached to the beams to increase sensitivity of the sensor or to render the sensor sensitive to acceleration and forces such as those arising from gravity, and magnetic and electric fields. The methods for sensing displacement of the beams can be capacitive or piezoresistive, or of other types, and the invention can be configured in various ways to adapt it to specific applications.

Brief Description of Drawings

Fig. 1 is a top view of the main body of the Three Beam One Aperture Force Sensor Embodiment.

Fig. 2 is an oblique view of the main body of the Three Beam One Aperture Force Sensor Embodiment.

Fig. 3a is a cross sectional view of the main body of the Three Beam One Aperture Force Sensor Embodiment taken at 3A-3A′ in Fig. 1 and shows the capacitor plates for a dual Dual Mode Capacitor Sensor Element element.

Fig. 3b is a cross sectional view of the main body of the Three Beam One Aperture Force Sensor Embodiment taken at 3B-3B′ of Fig. 1 and shows the capacitor plates for a single mode capacitor sensing element.

Fig. 4 is a top view of the main body of the Three Beam One Aperture Force Sensor Embodiment with a Y directed force applied. A large displacement of one beam is shown.

Fig. 5 is a cross sectional view of the main body of the Three Beam One Aperture Force Sensor Embodiment taken at 3A-3A′ in a device identical to of Fig. 1 except where an additional substrate is incorporated and two dual mode capacitor sensor elements are incorporated and coupled to the response element as shown.

Fig. 6 is a cross sectional view of the main body of the Three Beam One Aperture Force Sensor Embodiment taken at 3A-3A′ of Fig. 1 where a supplemental mass is incorporated on the response element.

Fig. 7 is a cross sectional view of the main body of the Three Beam One Aperture Force Sensor Embodiment taken

at 3A-3A' of Fig. 1 where material responsive to an electric or magnetic field is incorporated on the response element.

Fig. 8 is a top view of the Three Beam Three Aperture Force Sensor Embodiment.

Fig. 9 is an oblique view of the main body of the Three Beam Three Aperture Force Sensor Embodiment.

Fig. 10 is a top view of the main body of the Three Beam Three Aperture Force Sensor Embodiment with piezoresistors incorporated on the beams (represented by resistor symbols).

Fig. 11 is an oblique view of the main body of the One Beam One Aperture Force Sensor Embodiment.

Fig. 12 is a top view of the One Beam One Aperture Force Sensor Embodiment.

Fig. 13 is a cross sectional view of the main body of the One Beam One Aperture Force Sensor Embodiment taken at A-A' in Fig. 12.

Fig. 14 is a cross sectional view of the main body of the One Beam One Aperture Force Sensor Embodiment taken at B-B' in Fig. 12.

Fig. 15 is an approximate frontal view of the One Beam One Aperture Inclinometer Embodiment.

Fig. 16 is a diagram of the One Beam One Aperture Inclinometer Embodiment mounted on a free standing robot and used for balance control. The angle of in the x direction is shown.

Fig. 17 is a diagram of a One Beam One Aperture Inclinometer Embodiment mounted on a free standing robot and used for balance control. The angle of tilt in the z direction is shown.

Fig. 18 is an oblique view of the Five Beam Five Aperture force Sensor Embodiment.

Fig. 19 is a top view of the Five Beam Five Aperture Force Sensor Embodiment.

Fig. 20 is an enlarged top view of a cantilever beam of the Five Beam Five Aperture Force Sensor Embodiment with an associated temperature compensating resistor.

Fig. 21 is a top view of the Five Beam Five Aperture Force Sensor Embodiment subject to severe bending of beams responding to a multiple components of force.

Fig. 22a is a cross-sectional view of the main body of the Five Beam Five Aperture Force Sensor Embodiment shown in Fig. 21 subjected to forces bending beams the same distance out_of_plane. The cross sectional-view is taken at A-A′ in Fig. 21.

Fig. 22b is a cross-sectional view of main body of the Five Beam Five Aperture Force Sensor Embodiment subjected to forces bending beams different distances out_of_plane. The cross-sectional view is taken at B-B′ in Fig. 21.

Fig. 23 is a top view of the main body of the Five Beam One Aperture Force Sensor Embodiment.

FIG. 24 is an oblique view of the main body of the Four Beam One Aperture Force Sensor Embodiment.

Fig. 25 is a top view of the main body of the Four Beam One Aperture Force Sensor Embodiment.

Fig. 26 is a cross-sectional view of the main body of the Four Beam One Aperture Force Sensor Embodiment of FIG. 25 taken along line A-A′.

FIG. 27 is an electrical schematic diagram of the interconnections of the piezoresistors and bridge circuitry of the Four Beam One Aperture Force Sensor Embodiment.

FIG. 28 is an electrical schematic diagram of the interconnections of the piezoresistors and bridge circuitry of the Two Dimension Resolving Four Beam One Aperture Force Sensor Embodiment.

Fig. 29 is a cross-sectional view of the main body of the Four Beam One Aperture Force Sensor Embodiment of FIG. 24 taken along line A-A′ with capacitor electrodes incorporated on the response element and the underlying substrate.

FIG. 30 is a top view of the Multiple Beam Two Aperture Force Sensor Embodiment.

FIG. 31 is an oblique view of the main body of the Three dimensional Five Beam Four Aperture Force Sensor Embodiment.

FIG. 32a is a cross sectional view of the vertical beam an its response element of the Three Dimensional Five Beam Four Aperture Force Sensor Embodiment taken at A-A′ in Fig. 31 and illustrating definition fabrication of the vertical beam.

FIG. 32b is a cross sectional view of the vertical beam and its response element of the Three Dimensional Five Beam Four Aperture Force Sensor Embodiment taken at A-A′ in Fig 31 and illustrating the fabrication definition of the response element.

Fig. 33 is a cross sectional view of the main body of the Three Dimensional Five Beam Four Aperture Embodiment showing the vertical beam configuration.

Fig. 34 is an oblique view of a Single Mode Capacitor Sensor Element.

Fig. 35 is a top view of the Single Mode Capacitor Sensor Method Element capacitor plates.

Fig. 36 is an oblique view of a Dual Mode Capacitor Sensor Element, beam and response element.

Fig. 37 is an oblique view of the capacitor plate arrangement for the Dual Mode Capacitor Force Sensor Element of Fig. 36.

FIG. 38 is an top view of the Dual Mode Capacitor Sensor Element conducting plates where the response element has been displaced by a force having force components in the X and Z directions.

FIG. 39 is an oblique view of the Dual Mode Capacitor Sensor Element conducting plates of Fig. 38 where the response element has been displaced by a force with components in the X and Z directions, as in Fig. 38..

Fig. 40 is a top view of the Dual Mode Capacitor Force Sensor Element capacitor plates for a Special Geometry Capacitor Sensor Element.

Fig. 41 is a top view of the capacitor plates for another Dual Mode Special Geometry Capacitor Sensor Element.

Fig. 42A is a top view of 2 sets of electrically interconnected metallic plates of stripe geometry. The capacitor plates are plates each a part of each of the two capacitors for a Dual Mode Capacitor Sensor Element.

Fig. 42B is a top view of electrically interconnected metallic capacitor plate of stripe geometry. The capacitor plate is the common plate for the two capacitors of a Dual Mode Capacitor Sensor Element. The capacitor plates are two plates of a Stripe Geometry Dual Mode Capacitor Sensor Element.

Fig. 43 is a top view of the overlap of the two sets of stripe capacitor electrodes of Fig. 42 showing alignment and capacitor plate overlap before displacement occurs.

Best Modes for Carrying Out the Invention

1. THREE BEAMS-ONE APERTURE

One preferred embodiment of the present invention is a multibeam linear force sensor which uses capacitive sensing elements. Three components of linear acceleration are resolvable with the device.

Referring to Fig. 1, shown is the top view of the main body 130. Cantilever beams 132, 134, and 136 support response elements 138, 140, and 142, respectively, in a cavity 143 etched in the main body 130. The main body 130 is attached to a substrate 144, which contains stationary conducting plates 146, 148, 150, 152, and 154, each of which forms one plate of a capacitor. The substrate material may consist of glass, silicon, or other suitable materials.

Referring to Fig. 2, shown is an oblique view of the main body 130. Cantilever beams 132 and 134 are arranged orthogonal to each other, and are designed with the same thick, narrow cross section allowing easy lateral, i.e., substantially planar, displacement. Cantilever beam 136 is designed to be thin and wide, allowing easy non-planar

displacement. Beam 132 can bend due to forces along the X axis, beam 134 can bend due to forces along the Y axis, and beam 136 can bend due to forces along the Z axis of the coordinate system 156. The extreme aspect ratio (<<1 or >>1) of the cantilever cross section dimensions (the aspect ratio is defined as the beam width to thickness) results in negligibly small displacements in directions other than those desired. Where the two dimensions of a rectangular cross section of a beam are substantially different, the beam is relatively easily displaced in the direction normal to the wide dimension and is hard to displace, i.e., displays essentially negligible displacement in the other two directions due to applied forces. Fig. 4 shows the Three Beam One Aperture embodiment with beam 134 substantially bent due to an applied force with the other beams exhibiting negligible displacement in response to the same force. (The displacement of beam 134 in this example is severe and would introduce non-linear features, which can be compensated for with design of capacitor plate geometry or with suitable electronics, or with computer assisted treatment of the sensor element measurement data).

Referring to Fig. 3a, shown is a cross sectional view of the main body 130 taken at 3A-3A′ of Fig. 1. Response element conducting surface 158 forms one plate of a "dual mode" pair of capacitor sensing elements. The dual mode capacitor pair provides a quantitative measure of both direction and magnitude of displacement of a response element in two directions. The device can be used to measure either of the directions in which the response element is displaced or both of these displacements simultaneously. While the multicapacitor arrangement shown in Fig. 3a shows only two capacitors, multiple capacitor arrangements of more than two capacitors functioning on similar principles can be devised.

Fig. 3b is a cross-section taken at 3B-3B′ in Fig.1 and shows a single mode capacitor. Capacitor plate 161

is located on the bottom of response element 142. Capacitor plate 154 is located below capacitor plate 161 and is substantially larger than capacitor plate 154 in order to be substantially insensitive to motion along the x direction. Displacement of response element 142 in the z direction results in a capacitance change which is directly dependent upon the z directed force magnitude.

Fig. 5 is a cross-sectional view of response element 138 showing two dual capacitor sensor elements made up of capacitor plates. The first dual capacitor sensor element is made up of plates 146 and 158, and 148 and 158; the second dual capacitor mode sensing element consisting of plates 153 and 155, and 153 and 157. Both dual mode capacitive sensors measure y and z response element displacement. The advantage of using two dual mode capacitor sensors is to provide a reduction in measurement error.

The addition of a second substrate 160 can also be used in this and in other embodiments to form a casing (with parts 130 and 144) for limiting response element displacement. The casing can also provide containment of a fluid for damping purposes. Similar casings are also possible.

A further attractive feature of the capacitive sensing elements described is that they can be used simultaneously with piezoresistive sensing elements on the same beam-response element combination. This may have advantages in reducing measurement error in providing independent sensing elements which permit an increased number of simultaneous and separable force component measurements, and in building in more than one dynamic force measurement range in the same beam-response element combination.

Referring to Fig. 6, shown is a cross sectional view of the main body 130 taken at 3A-3A' of Fig. 1. A supplemental mass 162 may be attached to the response element to shift the center of mass to the plane of the

cantilever beam 136 of Fig. 1, in order to minimize unwanted torque features.

Referring to Fig. 7, shown is a cross sectional view of the main body 130 taken at 3A-3A′ of Fig. 1. Magnetic or electric field responsive material 164 is incorporated on the response element. For example, the electric field responsive material may be a high dielectric constant polymer or a charged or uncharged plate; the magnetic field responsive mateial may be magnetizable, such as iron, or a permanently magnetized material such as permalloy.

The beams of this present embodiment of the invention are designed to point inward for minimization of the effective undesirable moment arm forces or rotational origins. The three beam one aperture embodiment is intended to be used to measure linear forces such as linear acceleration and is not designed to be insensitive to forces of angular character such as centrifugal force or rotational acceleration forces.

Capacitance can be measured using various circuits and electronics such as oscillators or charge amplifiers. Such circuitry may be incorporated on the main body 130 with standard integrated circuit technology when silicon is used to fabricate device 131.

It is pointed out that the material of the device need not be a semiconductor. For example, quartz, glass or a ceramic material can be used. Here, capacitive sensing is used and the measurements are made in the same manner as described above. The quartz can be etched to shape using photolithographic techniques and etching techniques. Piezoresistors can be deposited on the beams, e.g., using CVD silicon technology, and for suitable orientation, the piezoelectic properties of quartz can also be incorporated. In the case of ceramics, ceramic structures can be formed using solgel technology and suitable forms. These forms can be micromachined out of silicon or other materials. Capacitor plates can be constructed using metal deposition techniques and

photolithographic techniques. Glass substrates can be machined and structured in a manner similar to that of quartz. In certain instances, quartz, glass, or ceramic material may be the preferred material because of elasticity, resistance to chemicals, magnetic properties, insulating properties, etc.

For capacitive sensing, there may be one or more capacitors associated with each response element or beam (the preferred location for the capacitor plate(s) is on the response element but capacitor plate(s) can also be located on the beam). Special shapes of the conducting pads may be used for desirable capacitance features such as a particular power dependence of capacitance change on applied force or for non-linear compensation or for directionality information. For example, if large beam displacements occur for beams 132 and 134, the shape of the capacitor plates 150, 152, 159 (Fig. 4) can be curved so that the bending of the beam still provides a linear relationship between displacement and capacitance change. Similarly, non-linear bending effects of the beam can be compensated for by using a suitable capacitor plate geometry (first order effects should be linear, second order effects should be quadratic, etc.). That is, the capacitor plate geometry can provide an inverse transformation of non-linear device behavior to give an overall linear device output response to force.

For transverse motion of the beams, e.g., for deflection of response element 140 due to a Y-directed force component, the sensitivity of the dual mode capacitor sensing element can be enhanced by making plates 158, 146 and 148 into striped geometries as indicated in Figures 42A, 42B and 43.

For the dual capacitor striped geometry, the alignment of the stripes on the response element conducting plate 468 should align with the stripes on the two substrate conducting plates 464 and 466 in a manner to cause one of the two capacitances to increase and the other to decrease when the response element 468 undergoes

a lateral displacement, i.e., + or - Y-direction. For the single mode capacitive sensing element used with beam 132 of the three beam three aperture embodiment of Fig 1, a single capacitor with both plates constructed of a striped geometry would provide both force magnitude and force direction . The density of stripes directly affects the sensor element's sensitivity and dynamic measurement range. The stripes are designed such that the separation between the stripes is of a magnitude that is large compared to the separation between the two plates.

Additional stationary conducting plates may be incorporated on a second substrate 160 acting as a cover to sandwich the main body 130 between two substrates 144 and 160.

The cantilever beams also need not be fabricated in a common cavity Each may be fabricated within a separate cavity or all may use a common cavity.

The addition of electrically or magnetically responsive materials 164 to the response element allows the device to be utilized in sensing applications other than acceleration, such as for proximity detection, position extrapolation, fusing, and others. Electric and magnetic fields can be sensed. Additional beams can be incorporated into the structure 130 such that one set of beams can be used to measure force arising from one source, e.g., a magnetic field, while another set of beams measures a force arising from gravity.

2. THREE BEAMS THREE APERTURES

Referring to Fig. 8, shown is another preferred embodiment of the present invention. A multibeam force sensor 165 is designed for resolution of the components of angular acceleration when the angular acceleration is about a center of rotation 167 and where only angular acceleration (radians/sec^2) is present. Centrifugal force arising from angular velocity about the point of rotation 167 provides only radially directed forces and

therefore causes only tensile strain in beams 168, 170 and 172.

This embodiment 169 can be modified to also measure centrifugal force in addition to inertial force arising from angular acceleration by adding additional sensing elements to each of the beams (embodiment 171). In particular, adding a piezoresistor 181, 357 and 183 to each of the beams 168, 170 and 172 provides for the measurement of radially directed forces such as centrifugal forces arising from angular velocity effects. In this case the piezoresistors should have the symmetry of the beam. This latter design feature can be accomplished by placing piezoresistor 181, 357 and 183 at the center of each beam, e.g., a diffused resistor isolated by a p-n junction from the rest of the beam, or by using the beam itself as the piezoresistor. Here, an oxide coating can be grown on the silicon and a metal strip connected to a contact on the silicon response element mass. In this way the device can measure either only angular acceleration, i.e., the rate of change of angular velocity with respect to time, or, if only the piezoresistors are monitored, measure only centrifugal force, or, if both sets of sensor elements (capacitor and piezoresistive) are measured, the device can be used to measure both angular acceleration and centrifugal force. Since centrifugal force is dependent upon the angular velocity squared, measurement of the force induced change in the piezoresistors results in a measure of angular velocity. Therefore the device can also be used to measure angular velocity, e.g., such as the revolutions per minute of an electric motor. When the device is used to measure forces due to angular motion, the center of rotation is maintained at the center for rotation of the device 167. The device can respond to other forces such as those arising from linear acceleration and can measure such forces. However, the embodiment 171 represented in Fig. 10 is able to measure at most 6 independent force components since there are only six independent sensor

elements. An attractive feature of the angular accelerometer 161 represented in Fig. 9 is that it measures the three orthogonal components of angular acceleration independently of one another, each sensor element is sensitive to only one angular acceleration component and each sensor element is insensitive to centrifugal force. This provides a reduced measurement error as discussed herein with respect to the condition of a matrix representing the sensitivity of the various sensor elements (the "sensitivity matrix S"). Further, when the embodiment 171 represented in Fig. 10 is used (angular acceleration and angular velocity, i.e., centrifugal force, measurement), the three angular acceleration measurements are made independently of one another and also separately from the centrifugal force measurements. Further, for centrifugal force measurements, embodiment 171 provides an independent measurement of centrifugal force arising from rotation about the Y-axis. The ability of the embodiment 171 to provide a high degree of separation of measurement of the total number of force components (six in this case, i.e., three from angular acceleration and three from angular velocity) should reduce measurement errors associated with the individual force components when the force components are resolved from the sensor element measurements. Here the aspect ratio (width/length) is <<1 or >>1 in order to constrain physical displacement of the beam to essentially only the direction normal to the wide dimension of the beam at the point of attachment to the main body. This feature provides advantages with respect to measurement error as referred to above. It is generally desirable to measure only one component per beam when practical. Thus, device 169 is designed to be used for the measurement of angularly rotating forces, e.g, to measure angular acceleration about the X, Y, and Z axes 173. And the device is designed to measure independent components of angular velocity, and independently angular acceleration.

Here the dual capacitor element is referred to as a single sensing element even though it senses displacement in two dimensions. Also, the four plate capacitor element which provides sensing using three capacitors is referred to in this discussion as one sensing element since it is of a particular type, namely capacitive, and for convenience of discussion, even though the four capacitor structure measures displacement in two cartesian dimensions. For beams which are constructed of sufficiently elastic material, e. g., from a suitable polymer, a capacitor array (i.e., sensing element) which provides measurement of displacement in three cartesian coordinates is easily constructed from a five capacitor array following the principles of the dual capacitor sensing element described herein. And, any of these capacitor sensing structures are termed in this context as a single sensing element, in particular, a capacitive sensing element.

The embodiment represented in Figs. 8 and 9. uses a single mode capacitor sensing element, a dual mode capacitor sensing element and a piezoresistive sensing element.

Fig. 8 shows a top view of the main body 166 for the device 169, with cantilever beams 168, 170, and 172 supporting response elements 174, 176, and 178, respectively. Each cantilever beam/response element is located within a separate etched cavity in the main body 166. A substrate 180 is attached to the main body and contains stationary capacitor conducting plates 182, 184, 186, and 188, each of which forms one plate of a capacitor. The respective complementary conductive capacitor plates which form the respective capacitors are conductive plates 175, 177, and 179, respectively, and are attached to the response elements 174. 176. and 178 in this example.

Fig. 9 shows an oblique view of the main body 166. Cantilever beams 170 and 172 are arranged to be projecting substantially orthogonal to each other at the

junction to the main body, and are designed with the same wide, thin cross section allowing easy non-planar displacement. Cantilever beam 168 is designed to be narrow and thick, allowing easy lateral displacement and is arranged to project substantially orthogonal to the projection direction of beam 172. Beam 170 can be deflected by rotational acceleration about the X axis, beam 172 be deflected by rotational acceleration about the Y axis, and beam 170 can deflected by rotational acceleration about the Z axis of the coordinate system 175. Each beam deflects in response to substantially only one orthogonal component of rotational acceleration, i.e., to rotational acceleration about the X. Y, or Z axes. The beam deflections are essentially insensitive to centrifugal forces for rotation about the rotation center location. For embodiment 165, when using the capacitor sensing elements, beam deflections correspond to response element deflections which alter the capacitances of said capacitor sensing elements.

The cantilevers need not be fabricated in separate cavities, and may be fabricated in a common cavity as long as a moment arm exists for rotational force components. Separate cavities have the advantage of providing convenient casings or portions of casings in which obstructions can be located to limit excessive beam and response element displacements. Said portion of a casing can be used together with additional structure located on the substrate to prevent device damage arising from excessive force and excessive displacement.

Device 171 in Fig. 10 is an embodiment which can measure angular acceleration forces and centrifugal forces simultaneously, as described above. The structure is identical to device 169 except that three additional sensing elements, piezoresistors 181, 183, and 357, have been added. These piezoresistors are made such that they respond principally to longitudinal forces directed along the axes of the beams. Such piezoresistors can be constructed by making the force sensor out of silicon and

using the beams themselves as piezoresistors, or by diffusing an impurity of the opposite type as that of the beam material (e.g, phosphorus if the beam material is originally doped with boron) from all sides of the beam such that the pn junction confined piezoresistive core is symmetrical about the beam axis.

Where both angular acceleration (or force) and centrifugal force components are desired to be measured, the use of additional sensor element applied to the structure of Fig. 8 is required. Piezoresistive and capacitive sensing elements on each beam and response elements combination can be used. The embodiment with both capacitive and piezoresistive sensing elements is represented in Fig. 10 where the resistors are represented by the usual notation for resistors for clarity (these resistors in practice may be diffused or deposited resistors).

Device sensitivity can be increased or decreased by changing the capacitor plate separations and capacitor plate areas and by using stripe capacitor plates as described herein and selection of beam cross sectional dimensions and dimensions of the response element. These adjustable design parameters provide a convenient set of design features to be used in tailoring the sensors for targeting particular force magnitude and sensitivity ranges and measurement error features.

3.ONE BEAM ONE APERTURE

In another preferred embodiment of the present invention, a single beam force sensor can be used for resolution of the components of linear forces. Both capacitive and piezoresistive sensing is used. Three independent components of linear force can be measured using this single beam single aperture device 191 shown in Figs. 11, 12, 13 and 14. By incorporating a high degree of independent sensing, that is, by using sensors such that orthogonal force components can be measured independently, and the third force sensed by a sensor element which measures two components of force

simultaneously, the measurement error associated with multiple force, multiply responsive response elements can be minimized compared to the situation where each sensor element measuring component is sensitive to all three forces.

Referring to Fig. 11, shown is an oblique view of the main body 192. The cantilever beam 194 can be fabricated with an essentially square or rectangular cross section, allowing beam 194 to have similar displacement magnitude arising from Z directed forces of similar magnitudes applied to response element 196 in co-ordinate system 206.

Referring to Fig. 12, shown is a top view of the main body 192. Cantilever beam 194 supports response element 196 which can be made with a substantially square cross section, or with a suitable ratio of width to height chosen with sensitivity and other performance considerations in mind. The cantilever beam 194 and response element 196 are formed within a cavity etched in the main body 192. A substrate 198 is attached to the main body and contains stationary conducting pads 200, 202, and 204, each of which forms one plate of a capacitor. The complimentary plate 197 of each of these capacitors is placed on the bottom side of the response element 196 in proximity to and substantially parallel to capacitor plates 200, 202, and 204. Fig. 11 represents the geometry of the device.

Referring to Fig. 13, shown is a cross sectional view of the main body 192 taken at A-A' of Fig. 12. Response element conducting surface 208 forms one plate of the combination of the dual mode and single mode sensing capacitors. Stationary conducting plates 200 and 202 form the other plates of the dual mode sensing capacitors, and stationary conducting pad 204 forms the other plate of a single mode sensing capacitor. The stationary conducting pads are located on the substrate 198.

Referring to Fig. 14, shown is a cross sectional view of the main body taken at B-B' of Fig. 12. A piezoresistor 210 is located at the center of beam 194. The resistor can be fabricated on beam 194 by simply using the beam itself as the resistor when the device is fabricated from silicon. Alternatively, the resistor can be formed by diffusing an impurity of the opposite type into the beam equally from all directions such that the resistor is centered on the axis of beam 194. For example, if the beam is of p-type silicon, an n type diffusion can be used to form a p-n junction by diffusing phosphorus or arsenic impurities. The beam itself can be etched down from a larger cross-section beam using a silicon etchant. The beam can be square or rectangular or oval or of another shape as determined by design and fabrication procedures.

Thinning of the beam using a silicon etchant may tend to convert the rectangular beam shape to one with rounded corners. Performance specifications are easily achieved by employing calibration procedures incorporating known forces.

The square cross section of the beam 194 allows displacement of the response element 196 in any of the three principal axes of the coordinate system 206. Forces directed along the X axis are measured by differential mode capacitive sensing. Plates 208 and 200 form one capacitor, and plates 208 and 202 form another capacitor. The changes in the overlapping area of the plates are used to determine X directed forces.

Plates 208 and 204 form a single mode sensing capacitor. Changes in the separation between the plates are used to determine Z directed forces.

The piezoresistor 210 is centered on the beam 194, and thus is sensitive only to axial displacement, i.e. strain, (along the Y axis) of the response element 196. Forces directed along the Y axis of the coordinate system 206 place the piezoresistor into tension or compression, and change the resistance in direct proportion to the

induced strain. By monitoring the magnitude and sign of the resistance change, Y directed forces may be measured. Thus, three components of linear force may be resolved with a single beam force sensor.

Each beam with its multiple sensor elements can be used in an array of a multibeam, multiforce sensor to measure forces of multiple types, i.e., origins. Here, each beam has the capability of discriminating among three orthogonal components of linear force. The organization of an array of beams and response elements can be selected such that the determinant of the sensitivity matrix S is non-zero. In this manner an array of said beams and response elements can be assembled to measure the three components of forces of more than one origin, e.g., linear, angular and centrifugal forces, and of forces of field origins such as derived from magnetic and electric field interactions.

For forces of sufficient magnitude that the displacement of the response elements are so large that the force component directed in the Y direction affects the response element displacement in the Z direction and the X direction, the measurement of the two force components in the X and Z directions may not be independent. However, by minimizing the sensitivity of the measurement of the X and Z displacements to the Y directed force, the overall measurement errors may be reduced. In mathematical terminology, this corresponds to minimizing the off diagonal elements of the sensitivity matrix S and maximizing the on diagonal elements.

Stated otherwise, the sensitivity of a sensor element should be maximized for a particular stimulus, i.e., a force component in this case, and the sensitivity to all other independent components of force components minimized. (Here maximum sensitivity and minimum sensitivity describe the relative sensitivities when the sensitivities are compared to one another and do not necessarily refer to absolute sensitivities.) For example, a sensor element should be made sensitive to

only one force, and totally insensitive to other independent components of force. The next best case is to make a sensor element maximally sensitive to one component of the force and minimally sensitive to the remaining independent force components. For example, a sensor element which is sensitive to a Y directed force and insensitive to X and Z directed force components is desirable. The piezoresistor for embodiment 197 meets this criteria for small displacements.

4. ONE BEAM ONE APERTURE INCLINOMETER EMBODIMENT

Control of the position of a free standing robot and other systems which are subjected to tilting forces requires a device to measure the orientation of the system. A robotic system is referred to here by way of example (Figs. 15, 16 and 17). However, the discussion applies to many different types of systems which require knowledge of their orientation with respect to a fixed reference. By way of example, the reference system for the free standing (or tethered) terrestrial robot is conveniently oriented with the direction of gravity. The robot must have some sort of a balancing system mechanism (as do humans) in order to maintain an orientation with respect to a fixed reference system such as gravity.

Fig. 15 illustrates a One Beam One Aperture Inclinometer Embodiment. The main body 801 is comprised of a single beam 378 projecting into a single aperture. The beam is attached to the main body 801 on one end and attached to response element 380 on the other end. A conductive plate 386 (not shown) is mounted on the response element. A complementary pair of conductive plates 382 and 384 are mounted on a substrate 388 in close proximity to the conductive plate 386. For an inclinometer, tilt in two directions is needed. A single beam device with a dual capacitor sensor element structure (Fig. 15), a single beam device with a three capacitor sensor element, a single beam device with a two or three capacitor sensor element and a piezoresistor (Figs. 13 and 14), or any of the various embodiments

described herein and which measure two orthogonal components of force can be used as an inclinometer sensing device. The preferred device has the minimum error associated with the force measurements.

5. FIVE BEAMS FIVE APERTURES

In another embodiment of the present invention, five cantilever beams can be used with piezoresistive sensing for the complete separation of nine independent force components when both angular and linear forces may be present: three dimensions of linear acceleration, three dimensions of angular velocity (resulting in centrifugal force and a corresponding acceleration representation), and three dimensions of angular acceleration. (While the example used to described the devices does so in terms of acceleration as the type of force under consideration, the explanation of the application of the device and its extension to influence by other types of force is analogous. For example, forces due to applied electric or magnetic fields can also be measured with the five beam embodiment.) It is noted that it is convenient to represent angular acceleration in terms of angular velocity squared in order to compress the dimension of the arm from the center of mass to the center of rotation into the sensitivity matrix S coefficients where it is easily incorporated via calibration measuring the S matrix coefficients, thus avoiding the need to measure said arm experimentally. The result also is a measure of angular frequency which is often the quantity of interest to be measured, e.g., when a measure of rpms is desired.

Referring to the drawing in FIG. 18, the accelerometer consists of a main body 212 which may be constructed of p-type silicon and which provides a rigid support structure for the other components including the beams 214, 216, 218, 220, 222 of the multidimensional force sensor.

The essential components of the accelerometer include five flexible cantilever beams 214, 216, 218, 220, 222 attached to a main body 212. Attached to the

beams are five response elements which for this accelerometer application example are masses composed of silicon material. The response elements 244, 246, 248, 250, and 252 are responsive to the acceleration applied to the main body. In this embodiment of the device, the cantilever beams 214, 216, 218, 220, 222 are designed to have the beam thickness roughly equal to that of the beam width in order to maximize lateral flexing with respect to out-of-plane bending, i.e., the beams are able to bend in two directions.

To achieve a high degree of sensitivity, the beam thickness and width are kept relatively thin with respect to the thickness (z direction) of the response masses and are of a thickness also much less than the thickness of the support structure. Eight n-type piezoresistors 224, 226, 228, 230, 232, 234, 236, 238 are located on four cantilever beams 214, 216, 218, 220. (While p-type piezoresistors are often used because they are reported to be less temperature sensitive than n-type piezoresistors, the magnitude of the longitudinal piezoresistive effect for n-type piezoresistors is larger than the magnitude of the longitudinal piezoresistive effect for p-type piezoresistors and thus will be used in the present example.) The said four cantilever beams are oriented along the <100> crystallographic directions on a (100) wafer. The piezoresistive coefficient is maximized along the <100> equivalent crystallographic directions of silicon and theoretically the shear stress coefficients should be negligible for piezoresistors oriented along said <100> and equivalent directions, i.e., said shear stress components are theoretically zero in the <100> crystallographic directions. The fifth cantilever beam 222 is oriented along the <100> direction, i.e., at forty five degrees from the <100> direction and in the (100) plane. The <110> for the fifth beam is chosen because of sensitivity considerations. In the <100> direction, the n-type piezoresistive coefficient is relatively large which results in relatively good sensitivity to an

applied acceleration. If the resistor 240 in beam 222 is made p-type, then the <110> direction can be used for the orientation of the fifth beam because of a large piezoresistive sensitivity (of opposite sign to that of n-type silicon). Incorporation of a p-type piezoresistor with the other eight piezoresistors being n-type is accomplished using diffusion isolation. An alternative method of fabricating the piezoresistors is to deposit polysilicon resistors on the surface of said five beams. Using a (100) oriented wafer, the <100> and <110> directions are conveniently located 45 degrees apart, in the plane of the wafer. In this example of a five beam embodiment, all five cantilever beams 214, 216, 218, 220, 222 extend radially outward from the center of the accelerometer structure 242.

Each of the cantilever beams 214, 216, 218, 220, 222 is mass-loaded with response elements 244, 246, 248, 250, and 252 respectively. Inertial forces acting on the response elements 244, 246, 248, 250, and 252 induce bending of the cantilever beams 214, 216, 218, 220, 222 when the main body undergoes acceleration.

The response elements 244, 246, 248, 250, and 252 are defined and etched from a silicon substrate at the same time as the cantilever beams are etched. An orientation dependent (anisotropic) etchant is used to define the beams and response elements. When needed to increase sensitivity, additional mass can be placed on the response elements 244, 246, 248, 250, 252 by depositing lead or gold onto the said response elements.

Each of the cantilever beams 214, 216, 218, 220, and 222 contains a minimum of two stress sensing elements which are able to measure displacement in two dimensions except for cantilever beam 222 (Fig. 19) which has just one stress sensing element 240. Piezoresistors are used as the stress sensing elements in this example. The concept using two piezoresistors which are placed off axis along a beam to measure beam displacement has been reported by Oki and Muller (A.K. Oki and R.S. Muller,

"Integrated Polysilicon Tactile Sensor," IEEE Solid State-State Sensors Workshop, June 2, 1986, pp. 7- 9, incorporated herein by reference).

FIG. 20 shows an enlarged top view of a cantilever beam 214. The line B-B′ denotes the location of the attachment of the cantilever beam 214 to the support structure. The attachment of the beam to the main body 212 projects substantially parallel to the plane of the main body 212. In the nomenclature intended herein, the use of the word "planar" structure is intended to mean planar in the absence of stress on any of the beams and in the absence of applied force on any of the beams. When the device is in operation to measure applied force components, the beams may flex out of the plane of the body 212. The device is still termed planar because the projection of the beams 214, 216, 218, 220, and 222 at the point of joining to the main body is parallel to the main body 212.

The stress sensing elements used here are n-type piezoresistors 224 and 226 diffused along the edges of and running along a partial length of the cantilever beam 214 (Fig. 20). Alternatively, p-type piezoresistors can be used, or deposited piezoresistors such as CVD deposited polysilicon piezoresistor can be used. The piezoresistors 224 and 226 are aligned along the <100> equivalent directions to take advantage of the maximum longitudinal piezoresistive effect which occurs for n-type resistors oriented along said <100> and equivalent directions thus providing the greatest sensitivity to acceleration derived forces. The piezoresistors 224 and 226 provide electrical signals representing the stress distribution developed in a bending cantilever beam. The electrical signals are substantially proportional to the acceleration of the main body when operating in the linear piezoresistance regime. It is pointed out that the piezoresistors 224 and 226 extend from the cantilever beam to the main body overlapping the region of maximum stress developed in the cantilever beam (where the line

B-B′ intersects the cantilever beam 214). Conductive return paths 254 and 256 can be fabricated with photolithographically defined deposited metals. External electrical contacts are made using bonding pads 258 and 260.

The resistor 262 located in the non-stress support region 212 acts as a temperature compensating resistor and is connected to bridge circuits along with the piezoresistor 224.

For sufficiently large forces the beams can be substantially away from their axial projection directions and also bend out of the plane. Figures 21, 22a and 22b illustrate bending extreme bending.

In order for the accelerometer to successfully separate and measure all of the independent force components, the measurement information provided by the sensor elements must be sufficiently independent. Where a large number of force components are present and where more than one response element is responsive to a multiple of independent force components, there may be complexity in determining values of the individual force components (even if the design of a particular sensor provides sufficiently independent sensor element measurement information).

The five beam force sensor embodiment can be constructed in the manner described here using other sensing elements. For example, pairs of sensing elements which discriminate two independent force components where the two components are lateral and vertical force components (as for the piezoresistor pair configuration described above) can be used with the same beam architecture. In particular dual capacitor sensing elements can be used instead of the piezoresistor pairs. The dual capacitors can also be used together with the piezoresistor sensing elements or in a mix or simultaneously with the piezoresistor sensing elements where the sensor element configuration is chosen such that sufficiently independent sensor element measurement

information is provided as discussed herein. A mix of different types of sensor elements may be used to improve measurement accuracy, e.g., by reducing the condition number of the sensitivity matrix S, or by separating the various independent sensor stimuli (acceleration components in the example) into independent subgroups.

The use of sensor element duplication using multiple types of sensor elements may provide additional information which may be used to increase the accelerometer accuracy. For example, both dual capacitor sensing elements and piezoresistor sensing elements can be used on each of the five arms (an arm is defined here as a beam plus a response element) of the five beam five aperture embodiment.

6. FOUR BEAMS ONE APERTURE

In another embodiment of the present invention, four flexible beams with strain sensing piezoresistors are attached to a rigid support frame at one end and a central response element is suspended at the free end of each of the four beams. In this embodiment, a single response element is common to all four beams. This structure is similar to the free hanging cantilever beams described above and exhibits similar principles of operation. Thus, the consideration of this structure as an embodiment of the present invention is appropriate. Beams are deflected by acceleration or other forces which can induce displacement of the response element. For acceleration applications, the response element is a mass affecting the displacement of each beam.

Strain sensing piezoresistors are coupled to the beams. Circuitry is used to convert force induced piezoresistance changes to voltages and to provide for temperature compensation. Measured output voltages are used to determine the components of forces causing the response element displacement.

The Four Beams One Aperture embodiment measures up to three orthogonal components of linear force. The basic embodiment can be supplemented and modified using

special circuitry or capacitive sensing methods as will be discussed below.

Referring to FIG. 24, represented is an oblique view of the main body 298. The beams 302, 304, 306, and 308 each contain a U-shaped piezoresistor 310, 312, 314, and 316 (R1, R2, R3, and R4, respectively). The ends of each resistor are connected to signal conditioning circuitry 320, 322, 324, and 326 formed in the rigid support frame 298. The beams 302, 304, 306, and 308 are oriented along the X and Y axes of the coordinate system 318.

Referring to FIG. 25, represented is the top view of the accelerometer main body 298. A response element 300 is suspended within an etched cavity 299 by flexible beams 302, 304, 306, and 308. Piezoresistors 310, 312, 314, and 316 are located on beams 302, 304, 306, and 308 respectively, and are designated as R1, R2, R3, and R4, respectively. The resistors are connected to signal conditioning circuitry 320, 322, 324, and 326 located in the rigid support frame 298 of the main body 298.

Referring to FIG. 26, represented is a cross sectional view of the main body 298 taken at A - A′ of FIG. 25. The response element 300 is deemed to include material above and below the plane of the supporting beams 304 and 308 and its center lies on, or close to, the beam axis projection from the beam at the connection to the response element. The response element 300 is much thicker than the supporting beams 304 and 308. The response element 300 is displaced relative to the rigid support frame 298 as the main body 298 undergoes acceleration or when a force is applied or induced to the response element.

Referring to FIG.27, represented is an electrical schematic diagram of the bridge circuitry used to convert resistance changes to voltages. Four Wheatstone bridges 328, 330, 332, and 334 are used. Bridge resistors 336 are formed on the rigid support frame of the device, and

are connected in four circuits to beam piezoresistors 310, 312, 314, and 316.

Referring to FIG. 28, represented is an electrical schematic diagram of the bridge circuitry of a Two-Dimension Resolving Configuration arranged to convert resistance changes to voltages and to provide a measurement of two orthogonal force components in the plane of the main body 298. Two special bridge circuits 338 and 340 are used. Bridge resistors 336 are formed on the rigid support frame of the device, and are connected in two circuits to beam piezoresistors 310, 312, 314, and 316. Two axially aligned piezoresistors (310 and 314 or 312 and 316) are connected in each bridge circuit to achieve additional features using this embodiment as described below.

Referring to Fig. 29, represented is a cross sectional view of the main body 298 when a single mode capacitor is included between the response element 300 and a substrate 340.

In-plane displacement of the response element from its rest position causes the axially aligned beam resistors R1 and R2 (310 and 314) to undergo opposite sign strains for the X directed force components. Induced tension and compression in the two beams aligned along the X-axis result in piezoresistive changes of opposite signs in resistors R1 and R2 (310 and 314). Axially aligned beams 304 and 308 are also deflected along the X-axis, but the resistances values are not affected because the strain components should cancel out. Due to beam and piezoresistor symmetry, there is zero net resistance change in the transversely strained piezoresistors R3 and R4 (312 and 316). Axially aligned beam resistors R3 and R4 are sensitive to Y directed axial force components orthogonal to the sensitivity axis of R1 and R2. Piezoresistors R1 and R2 are not sensitive to transverse force components along the Y-axis. Piezoresistors R3 and R4 are not sensitive to transverse force components along the X-axis .

Out-of-plane (Z directed) displacement of the response element causes all of the beam resistors to deflect in the same direction. Thus, resistance values of piezoresistors R1, R2, R3, and R4 (310, 312, 314, and 316) change by the same sign and magnitude in this case.

Each piezoresistor extends no more than one half the beam length, exploiting the bending stress distributions in the beams when the response element is subject to an out-of-plane force. The surface stress distribution in the beams of this embodiment inverts at approximately one half of the beam lengths when an out_of_plane force is applied. Thus, at the surface (where the resistors are generally located) one half of the beam is in tension while the other half of the beam is in compression when Z directed force components deflect the response element out_of_plane. By restricting the piezoresistors to the half of the beams nearest the support frame of the main body, +Z directed force components will induce only compressive forces into the piezoresistors. Force components directed along the -Z direction induce only tensile forces into the piezoresistors. A combination of tensile and compressive forces could reduce piezoresistive sensitivity if simultaneously applied to a piezoresistor. Because of the strategic placement of the resistors on the flexible beams, + Z directed acceleration components induce resistance changes of opposite sign to -Z directed forces.

When the center of mass of the response element is located in the same plane as the supporting beams axes (planar configuration), torque effects on the response element due to linear forces are minimized.

If the response element's center of mass is not co-linear with the axes of the beams, torque effects may be present. In certain applications, torquing of the response element can be used to enhance the sensitivity of the strain sensing piezoresistors by increasing strain. The effective torquing moment arm acting on the response element can be increased by locating the center

of mass of the response element off the axis of the beams. An example is the case where the beams are attached to the response element at its top side, such that the response element hangs below the plane of the beams.

Other beam and resistor designs are possible, including structures in which the beam material forms the piezoresistors themselves, and are formed with homogeneous material or by a resistive etch stop of diffused material. These designs and other related designs are considered structurally and functionally equivalent to the present invention.

The basic structure of this embodiment can be supplemented with a single mode capacitive sensing element between the response element 300 and the substrate 340. The capacitance of the electrodes 342 and 344 is varied with Z directed force components, but not significantly with X or Y directed force components. Capacitance measurements can be used to directly determine the Z directed force components independently of the piezoresistance measurements. Such a measurement may be used for redundancy of Z-axis force component resolving, a third dimension of resolution for the Two Dimension Resolving Configuration structure; or a reduction of the condition number of the system.

The circuit arrangement of this embodiment of Fig. 27 to out-of-plane sensitivity can be traded for other attractive features as described below. This configuration is called the Two Dimension Resolving Configuration, and utilizes a different bridge circuit design from that described above. The single mode capacitor described between the response element 300 and the underlying substrate 340 can provide an independent measure of the z-directed force component if needed.

In the Two Dimension Resolving Configuration, two piezoresistors are connected in each of two bridge circuits 338 and 340. This arrangement of resistors trades off out_of_plane piezoresistive sensitivity for

other desirable performance features. The output voltage of bridge circuit 338 is directly proportional to X directed force components, and no computations need be performed to obtain directly scaled force component measurements. Similarly, the output voltage of bridge circuit 340 is directly proportional to Y directed force components.

Advantages of the bridges in the Two Dimension Resolving Configuration over a standard Wheatstone bridge include a doubling of sensitivity and a linear output when operating in the piezoresistance linear region. Fabrication requirements are eased since bridge resistor values need not be closely matched to piezoresistor values, thus increasing tolerance to resistor variation. Adverse temperature sensitivity should be virtually eliminated with this circuit configuration.

The piezoresistors are designed to change in value by the same magnitude, same sign for out-of-plane force components and same magnitude, opposite sign for in-plane force components. Under these conditions, the bridge circuit outputs are sensitive only to phenomena causing opposite sign resistance changes in R1 and R2 (310 and 314) or R3 and R4 (312 and 316). Only X and Y directed force components cause such resistance changes (neither temperature effects nor Z directed forces are likely to cause opposite signed resistance changes in R1 and R2 or R3 and R4).

With directly scaled outputs, linear bridge response, and temperature insensitivity, the Two Dimension Resolving Embodiment suggests simple and reduced instrumentation costs in some applications. Planar force components are measured while out_of_plane force components do not substantially influence the device output.

The basic structure of both the two and three dimension resolving Four Beam One Aperture embodiment configurations minimize sensitivity to in-plane rotational errors when the rotation is about an axis

passing through the center of mass of the response element. Displacement stops can be built into the packaging to protect the device from damage due to excessive force application.

7. MULTIPLE BEAMS TWO APERTURE EMBODIMENT

Referring to FIG. 30, shown is the top view of another embodiment of the present invention. Two arrays of beam resistor pairs 350 and 352 are formed within etched cavities 318 and joined by response elements 354. Corresponding beam piezoresistors 366, 364, 370, and 368 are connected together, and are contacted on the rigid frame 348.

The Multiple Beam Two Aperture Embodiment is designed for increased force measurement resolution by increasing the effective piezoresistive lengths. Dual beam structures are utilized for efficient packing of etched cavities. Two arrays of etched cavities are used, each with series combinations of resistors. One array contains piezoresistors 366 and 364 corresponding to R1 and R2 (310 and 350 respectively) of the Four Beam One Aperture Embodiment. An orthogonal array contains resistors corresponding to R3 and R4 (312 and 352 respectively) of the Four Beam One Aperture Embodiment.

8. THREE DIMENSIONAL FIVE BEAMS FOUR APERTURES EMBODIMENT

FIG. 31 illustrates a Three Dimensional Five Beams Four Aperture embodiment 372. The main body 374 of the Three Dimensional Five Beams Four Aperture embodiment is comprised of four beams 806, 397, 395, and 399 which lie substantially in the same plane as the main body 374 when the sensor is not subjected to applied force. A fifth beam 353 attached to the center of the main body 374 is directed out of the main body's plane. The material of the main body and the beams may be of semiconducting material such as silicon and germanium, or of materials classified as quartz, glass, or ceramics. The attachment of the fifth beam 353 may be accomplished by silicon to silicon bonding with indium.

The response elements 351, 802, 390, 392, and 394 attached to the free ends of the cantilever beams 806, 397, 395, and 399, respectively, may be of the same materials used for the main body 374. The beams 351, 397, 395, and 395 and the response elements 351, 802, 390 and 392 are defined from the main body 374 using an anisotropic etchant. The fifth beam 353 and the associated response element 394 are defined and etched from a different substrate 396 and then mounted onto the main body 374. Supplemental materials such as gold may be mounted on the response elements 351, 802, 390, 392, and 394 to increase the response elements' sensitivity to force.

The sensing elements 375, 377, 379, 381, 383, 385, 387, and 389 are piezoresistors diffused into the surface of the p-type cantilever beams 806, 397, 395 and 399 are n-type. (p-type piezoresistors could be used instead of n-type). The piezoresistors are of opposite conductivity type from the main body 332. Alternatively, the sensing elements used could be capacitive in nature. For example, the "dual mode" capacitive sensing method described above could be used in place of the piezoresistors.

Industrial Applicability

The invention can be put to a wide variety of uses for the measurement of forces. For example, the invention could be used as an accelerometer that is capable of resolving all components of force acting on an object undergoing multidimensional acceleration, such as an out-of-control aircraft. Devices can be designed for linear acceleration and force measurement applications (such as x, y, and z directed linear forces), for centrifugal force applications and angular frequency measurement applications, and for angular acceleration applications. Devices can be designed to respond to field derived forces such as those originating from electric fields, magnetic fields, and gravitational fields. Other applications include automotive applications such as

control of automotive suspension. Vibration magnitude and frequency measurement, shock measurement, and measurement of magnitude and direction of magnetic fields are useful applications. MicroG and milliG applications for low G environment such as space, or in free fall situations, are also useful applications of the device. The ability to design sensitivity to selected force components where the device is sensitive to certain force components and less sensitive to other preselected components is an attractive feature of the device. Simultaneous measurement of forces of multiple origins is also useful. Many other useful applications exist where sensing more than one force component is desired.

The capacitor sensor element inventions are also attractive. Reduced temperature sensitivity, multidimensional resolving structures, increased sensitivity structures, and force selectivity sensing, are all attractive features. Compatibility with other sensing methods allowing for mixed sensor elements on a single beam and response element is additionally attractive and provides multidimensional force resolving features and, in appropriate instances, reduced measurement errors of the force.

With appropriately chosen design and response elements, the invention can be used to measure the magnitude and direction of gravitational, electrical or magnetic fields. The response elements may consist of an inertial mass, suitably coated with, or constructed of, conducting, dielectric, or magnetic material such that an electric, gravitational, or magnetic field causes a force on the response element. Electric, gravitational, and magnetic fields may be simultaneously measured by increasing the number of arms of suitable geometry so that one set of arms has response elements coated with or constructed of magnetic or magnetizable material, another set ofr arms has response elements coated with or constructed of electrically polarizable material, and a third set of arms has electrically and magnetically

nonresponsive but massive that respond solely to accelerating forces such as gravity.

A further use of the invention is in electric or magnetic field sensing devices for proximity detection, object tracking, and position monitoring. In the case of magnetizable and magnetic objects, this can be accomplished by, for example, choosing response elements that are magnetized so that the beams will be displaced by the proximity of said object. Such devices could be used for fuses in explosive devices.

A further use of the invention would be to measure magnitude and direction of drag such as arising from fluid motion. Examples include air and water motion drag on response elements and/or supporting beams.

A further use of the invention would be to provide inclination measurements, including use as the balance monitoring and sensing mechanism (similar to an inner ear) for free standing or tethered robotics and for vehicles such as automobiles, trucks, boats, ships, and aircraft.

The preferred embodiments described herein have been described in terms of fabrication from silicon material which is usually the material of choice because of large and available, advanced and controlled technology, and because the use of silicon provides a convenient substrate on which to integrate signal conditioning circuitry. However, the fabrication of the invention is not limited to silicon material.

DESIGN AND MEASUREMENT CONSIDERATIONS

Ill Conditioned Sensitivity Matrix: The Condition Number K

When more than one stimulus is to be sensed, e.g., more than one force component or more than one chemical (in the case of chemical sensing), more than one independent parameter must be measured. In general when N independent stimuli, e.g., force components, are to be measured, N sensor parameters must in general be measured and said N sensor parameters must have sufficient

independence to allow the N unknown independent stimuli (forces in this example) to be determined. When the number of stimuli is large and when the sensor elements respond to multiple independent stimuli, then the individual influences on the sensor elements must be deconvolved. That is, the measurement data must be manipulated to provide the values of the stimuli to be measured. The example of the five beam five aperture force sensing device embodiment described above illustrates the concept. Each of the nine piezoresistors responds to a large number of independent force components.

The use of the sensitivity matrix S and its inverse as described above provides a method for resolving out the various values of the force components from the sensor element measurements. However, this procedure can add measurement error to the measurement of the force components. The measurement error associated with the determination of the force components can be larger than the measurement error associated with each sensor element. The preferred device embodiment usually maximizes resolution and minimizes error associated with force resolution (measurement). Design of the device can reduce force measurement errors.

The condition number K provides an quantitative indication of the error introduced when using response elements which are sensitive to more than one stimuli, e.g., to more than one force component in the case of a force sensor, or to more than one chemical in the case of a chemical sensor. The condition number K provides a quantitative upper bound on the error which could be expected for a particular sensitivity matrix and therefore for the corresponding sensor design. That is, for a particular design, the error of measured force components should not be greater that a certain percentage which is characterized by the sensor element measurement error and the condition number K of the sensitivity matrix S.

This very useful feature of the condition number is discussed here by way of example for a force sensor. However, the concept extends to other sensors, in particular to chemical sensors.

A number of considerations can be deduced from consideration of the condition number: 1. The sensor elements and response elements are to be selected to be responsive to the minimum number of independent stimuli; 2. Where the sensor element is influenced by more that one independent stimuli, it is usually preferable to select the sensor element or response element and embodiment design such that the sensor element is substantially sensitivity to one said stimulus with the sensitivities to the other stimuli minimized. Each sensor of the sensor array should be thus chosen.

The Three Beam Three Aperture embodiment (with the piezoresistors incorporated on the beams) is an example. With this embodiment independent measurement of three components of angular acceleration and an independent measurement of one of the components of centrifugal force (acceleration) are made with the remaining two components of centrifugal force being mixed. The S matrix is diagonal except for a two rows of a submatrix. The error in the force measurement in this embodiment is usually less than the error associated with the five beam embodiment using piezoresistive sensing elements assuming that the sensing elements have equal sensitivities.

Determination of Device Capability for Resolving Independent Force Components

Where the intent is to simultaneously measure multiple force components in a single device, for successful and accurate application of the device it is necessary to insure that the sensor embodiment can separate the individual force components. This feature of a multiforce sensor can be characterized by inspection of the determinant of the sensitivity matrix S. Whether or not a sensor can measure all of the individual force components when many independent force components are

present can be non-obvious when multiple sensor elements are present and were some of sensor elements are responsive to a multiple of said independent force components. In this latter case the sensitivity matrix S is non-diagonal. If the determinant of the S matrix is zero, the sensor is unable to successfully measure all of the force components simultaneously when all of said force components are present.

When the determinant of the sensitivity matrix S is non-zero, the sensor described by said S matrix is able to simultaneously provide some measure of all the independent force components when all of the force components are simultaneously present.

Although the invention has been described with reference to certain preferred embodiments described in the accompanying drawings, the invention is not limited to those embodiments and various changes and modifications may be made by those skilled in the art without departing from the spirit or scope of the invention. Accordingly, no limitations are to be inferred except for those specifically set forth in the attached claims. Further, in the claims, "displacement" shall be deemed to mean and include "stress", "strain" and "deflection", and "mounted" shall mean and include "diffused." Also, a response element mounted at an intermediate location on a beam shall be deemed to be equivalent to a response element with two beams attached to it. A beam shall be deemed to be projecting in a direction if the beam is projecting in that direction at the point where the beam is attached to a main body or a post. An electrical signal shall be deemed to include a change in current, voltage, capacitance, resistance or inductance. Finally, "Housing" shall be deemed to mean and include "casing" and "substrate."

DESCRIPTION OF THE CAPACITIVE SENSING METHODS AND ELEMENTS

The embodiments of this invention are characterized as having one or more flexible beams coupled to response elements and sensing elements. One type of sensing method used with the embodiments of the present inventions is based on capacitive plate displacement effects. Single mode, dual mode and trimode sensors are described herein, together with finger shaped capacitor plates and capacitor plates of other geometric shapes, which can provide advantageous sensing elements.

There are three general approaches to capacitive sensing utilized in the present inventions. The Single Mode Capacitive Sensing method exploits the dependance of capacitance on the distance separating two conducting plates forming a capacitor structure. The single mode capacitor plate is represented in Fig. 34. The Dual Mode Capacitance Sensing method exploits the dependance of capacitance on the overlapping area of conducting plates forming a capacitor system which is made up of multiple capacitors. The dual mode capacitor is represented in Fig. 36. A special case of the dual mode capacitor sensing element is a two plate capacitor with the capacitor plates only partially overlapping in the absence of applied force and with the overlap changing when force is applied. The third capacitor sensing element described consists of four capacitor plates and is a combination of single mode and dual mode capacitors and is represented in Figs. 12 and 13.

Referring to Fig. 34, the Single Mode Capacitive Sensing Element 428 consists of a cantilever beam 432 supporting a response element 434. The cantilever beam 432 is attached to a support structure 433. The structure is mounted on a substrate 430. The single capacitor consists of two electrodes 436 and 438 shown in Fig. 34. The electrode 436 is mounted beneath the response element 434 in close proximity to the complementing electrode 438 mounted on the substrate 430.

The force components act on the response element 434 to deflect the cantilever beam 432 and the response element 434. The displacement is proportional to the force components and this moves the electrode 436 of the capacitor mounted beneath the response element. The displacement of the electrode 436 relative to electrode 438 mounted on the substrate is sensed by measuring the capacitance changes induced by the displacement of the electrode 436.

Referring to Fig. 35, the substrate electrode 438 is constructed to be larger than the response element electrode 436 when the supporting cantilever beam may be of a cross section that allows for significant lateral (X) movement of the response element as well as Z displacement. Lateral force components displacing the response element in the X direction will not have a significant effect on the capacitance between electrodes 436 and 438. Substantially only the Z component of displacement will be measured. Alternatively, the

supporting cantilever beam can be constructed with a cross section such that significant deflection can only occur along the Z axis. In the latter case, a structure responsive to Z axis directed force components (and essentially insensitive to X or Y axis directed forces) can use electrodes of the same area with either overlapping or partially overlapping plates.

A Dual Mode Capacitance Sensing Element 440 is shown in Figs. 36 and 37. The dual mode capacitors consist of two capacitors C_A and C_B comprised of three conductive plates 448, 452, and 450. Conductive plates 448 and 452 comprise one capacitor C_A and the conductive plates 448 and 450 comprise a second capacitor C_B. Multiple capacitor plates are used to increase the sensitivity. The electrode 448 is mounted beneath the response element 434 and the electrodes 452 and 450 are mounted onto the substrate 442.

If multiple sensing elements are placed on the same beam, for example, to minimize the number of beams necessary, the various sensing elements must have some "independent" features in order to allow resolution of independent force components. The sensing elements should be sufficiently independent if there is at least one direction in which displacement of the beam will cause the sensing elements to react differently.

When multiple sensing elements are placed on the same beam, independent response requires that each sensing element respond differently to at least one force

component. Independent response is achieved with the dual mode capacitor sensor and with the trimode capacitor sensor. Figs. 38 and 39 illustrate that lateral movement (in the negative X direction) of the response element 434 relative to the substrate 442 results in a decrease in the capacitance C_A due to a decrease in the overlap area A_A 455 of the electrode pair 448 and 452. A corresponding increase in the capacitance C_B results due to an increase in the overlap area A_B 453 of the electrode pair 448 and 450.

In contrast, a vertical force acting on the response element 434 changes the separation distance d between electrodes 448 and 452 and the separation d between electrode 448 and 450 by equal amounts vd. In this case, the percentage capacitances change in C_A and C_B are equal and related to the Z directed displacement of the response element 434.

Referring to Fig. 39, a change in the electrode separation is given by vd and or the change in the electrode overlap area is given by vA. The displacements vd and change in overlap area vA can be determined by measuring the capacitance changes in C_A and C_B. Directionality of the response element displacement can be measured. The displacements vd and vA are functions of the force components. A quantitative analysis relating the force and the displacement components is presented.

Directionality of the response element displacement is determined for the capacitance values C_A and C_B. The measured capacitance values C_A and C_B are compared with the reference values C_{A0} and C_{B0} which are measured in the absence of applied force, or in the presence of a known applied force such as the force of gravity. Response element displacement magnitude and direction can also be determined using capacitor plates of non-rectangular geometry such as those shown in Figs. 40 (458 and 460) and 41 (458 and 462).

The conductive plate geometry can also be used to create a particular power dependence, i.e., non-linearity of capacitance change on the beam displacement, or the force, to provide useful electrical nonlinearities. Such nonlinearities can be used to compensate for the nonlinear relationships between acceleration and strain, to measure ac components of force via harmonic operation of a signal derived utilizing capacitances, or for other useful purposes.

The capacitance change can be determined by measuring the capacitance directly, by measuring a related "RC" time constant, by measuring the frequency of a relaxation oscillator, or by using another sensing circuit where the electrical behavior of a sensing circuit is altered in a measurable way by a force induced capacitance change.

To increase the sensitivity for a force displacement of response element 446 can be advantageous to fabricate

a series of interconnected stripe capacitor plates such as those shown in Fig. 42a and 42b. A stripe capacitor plate 468 is mounted on the response element 446. A pair of stripe capacitor plates 464 and 466 are mounted on the substrate . In Fig. 43, the top view of the stripe capacitor plates illustrates the offset of the capacitor plates from each other due to the application of force on the response element. For example, for a lateral movement of the response element 446 of 1.5 micron for strip 468 width of 10 microns causes approximately a 15% capacitance change where as a 1500 micron wide rectangular capacitor electrode 448 would result in approximately a change 1.0 X 10-2% capacitance change.

Stripe capacitors are preferably designed with the strip width and strip separation greater than the separation between capacitor plates of a capacitor to minimize fringing field effects.

CLAIMS

We claim:

1. A multidimensional force sensor, comprising:
a main body;
a plurality of beams, each having a first end and a second end, said beams mechanically coupled at their first ends to said main body, said plurality of beams arranged in a substantially planar array; and
sensing means, coupled to each of said plurality of beams, for sensing displacement of each of said beams.

2. A multidimensional force sensor, as described in claim 1, further comprising;
a plurality of response elements, each attached to the second end of corresponding beams.

3. A multidimensional force sensor, as described in claim 2, wherein said main body is substantially planar.

4. A multidimensional force sensor, as described in claim 3, wherein said sensing means comprises a plurality of discrete electromechanical sensor elements, each sensor element producing an electrical signal in response to displacement of a single corresponding beam.

5. A multidimensional force sensor, as described in claim 4, wherein said plurality of sensor elements are mounted on corresponding ones of said plurality of beams.

6. A multidimensional force sensor, as described in claim 3, wherein said sensing means comprises a plurality of discrete capacitive sensor elements, each of which includes a movable plate and a fixed plate, each capacitive sensor element producing a change in capacitance in response to displacement of a single corresponding beam.

7. A multidimensional force sensor, as described in claim 6, wherein said movable plates of said plurality of sensor elements are mounted on corresponding ones of said response elements.

8. A multidimensional force sensor, as described in any one of claims 1 to 7, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

9. A multidimensional force sensor, as described in claim 8, wherein said semiconducting material is silicon.

10. A multidimensional force sensor, as described in claim 8, wherein said semiconducting material is germanium.

11. A multidimensional force sensor, as described in any one of claims 1 to 7, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

12. A multidimensional force sensor, as described in claim 2, further comprising limiting means partially surrounding one of said response elements, for limiting displacement of said one response element.

13. A multidimensional force sensor, as described in claim 12, wherein said limiting means comprises a casing.

14. A multidimensional force sensor, as described in claim 2, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

15. A multidimensional force sensor, as described in claim 1, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

16. A multidimensional force sensor, as described in claim 15, wherein said damping means comprises a fluid.

17. A multidimensional force sensor, as described in claim 1, wherein each of said beams is constructed so that displacement of each of said beams is substantially anisotropic with respect to force.

18. A multidimensional force sensor, as described in claim 17, wherein each of said beams is so constructed that each of said beams is substantially displaceable by a force in only one dimension and said dimension is different for each of said beams.

19. A multidimensional force sensor, comprising:

a substantially planar main body having an aperture;

a wide and thin first beam having opposing wide sides attached at a first end to said main body and projecting into said aperture in a direction substantially parallel to the plane of said main body, with the normal of the wide sides of said first beam oriented substantially perpendicular to the plane of said main body;

a wide and thin second beam having opposing wide sides attached at a first end to said main body and projecting into said aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said first beam, with the normal of the wide sides of said second beam oriented substantially parallel to the plane of said main body;

a wide and thin third beam having opposing wide sides attached at a first end to said main body and projecting into said aperture in a direction substantially parallel to the direction of said main body and substantially perpendicular to the direction of said second beam, with the normal of the wide sides of said third beam oriented substantially parallel to the plane of said main body; and

sensing means coupled to each of said first, second and third beams, respectively, for sensing displacement of each of said first, second and third beams, respectively.

20. A multidimensional force sensor, as described in claim 19, further comprising:

first, second and third response elements attached to the second ends of each of said first, second and third beams, respectively.

21. A multidimensional force sensor, as described in claim 20, wherein said sensing means is coupled to each of said first, second and third response elements, respectively, for sensing displacement of each of said first, second and third response elements, respectively.

22. A multidimensional force sensor, as described in claim 19, wherein said sensing means comprises first, second and third discrete electromechanical sensor elements, said first, second and third sensor elements producing electrical signals in response to displacement of said first, second and third beams respectively.

23. A multidimensional force sensor, as described in claim 22, wherein said first, second and third sensor elements are mounted on said first, second and third beams, respectively.

24. A multidimensional force sensor, as described in claim 21, wherein said sensing means comprises first, second and third capacitive sensor elements, each of which includes a movable plate element and a fixed plate element, each of said first, second and third capacitive sensor elements producing a change in capacitance in response to displacement of said first, second and third response elements, respectively.

25. A multidimensional force sensor, as described in claim 24, wherein said movable plate elements of said first, second and third capacitive sensor elements are mounted on said first, second and third response elements, respectively.

26. A multidimensional force sensor, as described in claim 19, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

27. A multidimensional force sensor, as described in claim 26, wherein said semiconducting material is silicon.

28. A multidimensional force sensor, as described in claim 26, wherein said semiconducting material is germanium.

29. A multidimensional force sensor, as described in claim 19, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

30. A multidimensional force sensor, as described in claim 20, further comprising limiting means partially surrounding one of said response elements for limiting displacement of said one response element.

31. A multidimensional force sensor, as described in claim 30, wherein said limiting means comprises a casing.

32. A multidimensional force sensor, as described in claim 20, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

33. A multidimensional force sensor, as described in claim 19, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

34. A multidimensional force sensor, as described in claim 33, wherein said damping means comprises a fluid.

35. A multidimensional force sensor, comprising:

a substantially planar main body having first, second and third apertures and a center of rotation about which said main body is adapted to rotate;

a wide and thin first beam having opposing wide sides attached at a first end to said main body and projecting into said first aperture in a direction substantially parallel to the plane of said main body and substantially outward from said center of rotation, with

the normal of the wide sides of said first beam oriented substantially perpendicular to the plane of said main body;

a wide and thin second beam attached at a first end to said main body and projecting into said second aperture in a direction substantially parallel to the plane of said main body, substantially perpendicular to the direction of said first beam and substantially outward from said center of rotation, with the normal of the wide sides of said second beam oriented substantially perpendicular to the plane of said main body;

a wide and thin third beam attached at a first end to said main body and projecting into said third aperture in a direction substantially parallel to the plane of said main body, substantially perpendicular to the direction of said second beam and substantially outward from said center of rotation, with the normal of the wide sides of said third beam oriented substantially parallel to the plane of said main body; and

sensing means for sensing displacement of each of said first, second and third beams, respectively, coupled to each of said first, second and third beams, respectively.

36. A multidimensional force sensor, as described in claim 35, further comprising:

first, second and third response elements attached to the second ends of each of said first, second and third beams, respectively.

37. A multidimensional force sensor, as described in claim 36, wherein said sensing means comprises sensing means coupled to each of said first, second and third response elements, respectively, for sensing displacement of each of said first, second and third response elements, respectively.

38. A multidimensional force sensor, as described in claim 35, wherein said sensing means comprises first, second and third discrete electromechanical sensor elements, said first, second and

third sensor elements producing electrical signals in response to displacement of said first, second and third beams respectively.

39. A multidimensional force sensor, as described in claim 38, wherein said first, second and third sensor elements are mounted on said first, second and third beams, respectively.

40. A multidimensional force sensor, as described in claim 37, wherein said sensing means comprises first, second and third capacitive sensor elements, each of which includes a movable plate and a fixed plate, each of said first, second and third capacitive sensor elements producing a change in capacitance in response to displacement of said first, second and third response elements, respectively.

41. A multidimensional force sensor, as described in claim 40, wherein said movable plates of said first, second and third capacitive sensor elements are mounted on said first, second and third response elements, respectively.

42. A multidimensional force sensor, as described in claim 35, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

43. A multidimensional force sensor, as described in claim 42, wherein said semiconducting material is silicon.

44. A multidimensional force sensor, as described in claim 42, wherein said semiconducting material is germanium.

45. A multidimensional force sensor, as described in claim 35, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

46. A multidimensional force sensor, as described in claim 36, further comprising limiting means

partially surrounding one of said response elements for limiting displacement of said one response element.

47. A multidimensional force sensor, as described in claim 46, wherein said limiting means comprises a casing.

48. A multidimensional force sensor, as described in claim 36, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

49. A multidimensional force sensor, as described in claim 35, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

50. A multidimensional force sensor, as described in claim 49, wherein said damping means comprises a fluid.

51. A multidimensional force sensor, comprising:

a substantially planar main body having first, second, third, fourth and fifth apertures;

a first beam attached to said main body at a first end and projecting into said first aperture in a direction substantially parallel to the plane of said main body;

a first sensor element for sensing displacement of said first beam, coupled to said first beam;

a second sensor element for sensing displacement of said first beam, coupled to said first beam, that responds differently from said first sensor element to displacement of said first beam in one direction;

a second beam attached to said main body at a first end and projecting into said second aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said first beam;

a third sensor element for sensing displacement of said second beam, coupled to said second beam;

a fourth sensor element for sensing displacement of said second beam, coupled to said second beam, that

responds differently from said third sensor element to displacement of said second beam in one direction;

a third beam attached to said main body at a first end and projecting into said third aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said second beam;

a fifth sensor element for sensing displacement of said third beam, coupled to said third beam;

a sixth sensor element for sensing displacement of said third beam, coupled to said third beam, that responds differently from said fifth sensor element to displacement of said third beam in one direction;

a fourth beam attached to said main body at a first end and projecting into said fourth aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said third beam;

a seventh sensor element for sensing displacement of said fourth beam, coupled to said fourth beam;

an eighth sensor element for sensing displacement of said fourth beam, coupled to said fourth beam, that responds differently from said seventh sensor element to displacement of said fourth beam in one direction;

a fifth beam attached to said main body at a first end and projecting into said fifth aperture in a direction substantially parallel to the plane of said main body and between said fourth beam and said first beam; and

a ninth sensor element for sensing displacement of said fifth beam, coupled to said fifth beam.

52. A multidimensional force sensor, as described in claim 51, further comprising:

first, second, third, fourth and fifth response elements attached to the second ends of said first, second, third, fourth and fifth beams, respectively.

53. A multidimensional force sensor, as described in claim 51, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

54. A multidimensional force sensor, as described in claim 53, wherein said semiconducting material is silicon.

55. A multidimensional force sensor, as described in claim 53, wherein said semiconducting material is germanium.

56. A multidimensional force sensor, as described in claim 51, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

57. A multidimensional force sensor, as described in claim 52, further comprising limiting means partially surrounding one of said response elements for limiting displacement of said one response element.

58. A multidimensional force sensor, as described in claim 57, wherein said limiting means comprises a casing.

59. A multidimensional force sensor, as described in claim 52, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

60. A multidimensional force sensor, as described in claim 51, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

61. A multidimensional force sensor, as described in claim 60, wherein said damping means comprises a fluid.

62. A multidimensional force sensor, comprising:

a substantially planar main body having an aperture;

a first beam attached to said main body at a first end and projecting into said aperture in a

direction substantially parallel to the plane of said main body;

a first sensor element for sensing displacement of said first beam, coupled to said first beam;

a second sensor element for sensing displacement of said first beam, coupled to said first beam, that responds differently from said first sensor element to displacement of said first beam in one direction;

a second beam attached to said main body at a first end and projecting into said aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said first beam;

a third sensor element for sensing displacement of said second beam, coupled to said second beam;

a fourth sensor element for sensing displacement of said second beam, coupled to said second beam, that responds differently from said third sensor element to displacement of said second beam in one direction;

a third beam attached to said main body at a first end and projecting into said aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said second beam;

a fifth sensor element for sensing displacement of said third beam, coupled to said third beam;

a sixth sensor element for sensing displacement of said third beam, coupled to said third beam, that responds differently from said fifth sensor element to displacement of said third beam in one direction;

a fourth beam attached to said main body at a first end and projecting into said aperture in a direction substantially parallel to the plane of said main body and substantially perpendicular to the direction of said third beam;

a seventh sensor element for sensing displacement of said fourth beam, coupled to said fourth beam;

an eighth sensor element for sensing displacement of said fourth beam, coupled to said fourth beam, that responds differently from said seventh sensor element to displacement of said fourth beam in one direction;

a fifth beam attached to said main body at a first end and projecting into said aperture in a direction substantially parallel to the plane of said main body and between said fourth beam and said first beam; and

a ninth sensor element for sensing displacement of said fifth beam, coupled to said fifth beam.

63. A multidimensional force sensor, as described in claim 62, further comprising:

first, second, third, fourth and fifth response elements attached to the second ends of said first, second, third, fourth and fifth beams, respectively.

64. A multidimensional force sensor, as described in claim 62, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

65. A multidimensional force sensor, as described in claim 64, wherein said semiconducting material is silicon.

66. A multidimensional force sensor, as described in claim 64, wherein said semiconducting material is germanium.

67. A multidimensional force sensor, as described in claim 62, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

68. A multidimensional force sensor, as described in claim 63, further comprising limiting means partially surrounding one of said response elements for limiting displacement of said one response element.

69. A multidimensional force sensor, as described in claim 68, wherein said limiting means comprises a casing.

70. A multidimensional force sensor, as described in claim 63, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

71. A multidimensional force sensor, as described in claim 62, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

72. A multidimensional force sensor, as described in claim 71, wherein said damping means comprises a fluid.

73. A multidimensional force sensor, comprising:

a support post;

first, second, third and fourth beams attached at their respective first ends near the top of said support post and projecting radially from said support post at a radial separation of approximately ninety degrees from each other;

a fifth beam attached near the top of said support post and projecting radially from said support post at a radial separation of approximately forty-five degrees from said first beam;

first, second, third, fourth and fifth primary sensor elements for sensing displacement of each of said first, second, third, fourth and fifth beams, respectively, coupled to said first, second, third, fourth and fifth beams, respectively; and

first, second, third, and fourth secondary sensor elements for sensing displacement of each of said first, second, third and fourth beams, respectively, coupled to said first, second, third and fourth beams, respectively, that respond differently from said first, second, third and fourth primary sensor elements, respectively, to displacement in one direction of said first, second, third and fourth beams, respectively.

74. A multidimensional force sensor, as described in claim 73, further comprising:

first, second, third, fourth and fifth response elements attached to the second ends of said first, second, third, fourth and fifth beams.

75. A multidimensional force sensor, as described in claim 73, wherein said support post and said beams comprise an integrally formed piece of semiconducting material.

76. A multidimensional force sensor, as described in claim 75, wherein said semiconducting material is silicon.

77. A multidimensional force sensor, as described in claim 75, wherein said semiconducting material is germanium.

78. A multidimensional force sensor, as described in claim 73, wherein said support post and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

79. A multidimensional force sensor, as described in claim 74, further comprising limiting means partially surrounding one of said response elements for limiting displacement of said one response element.

80. A multidimensional force sensor, as described in claim 79, wherein said limiting means comprises a casing.

81. A multidimensional force sensor, as described in claim 74, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

82. A multidimensional force sensor, as described in claim 73, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

83. A multidimensional force sensor, as described in claim 82, wherein said damping means comprises a fluid.

84. A multidimensional force sensor, comprising:

a main body having an aperture with a central region;

first, second, third and fourth beams, each having a first end and a second end, said beams mechanically coupled at their first ends to said main body, each of said beams projecting into the central region of said aperture in a direction substantially parallel to the plane of said main body;

a response element attached to the second ends of said first, second, third and fourth beams in the central region of said aperture; and

sensing means coupled to said first, second, third and fourth beams for sensing displacement of said first, second, third and fourth beams.

85. A multidimensional force sensor, as described in claim 84, wherein each of said beams is substantially perpendicular to its adjacent beams.

86. A multidimensional force sensor, as described in claim 84, further comprising a plate support member attached to said main body and extending towards said response element, a first capacitor plate attached to said response element, a second capacitor plate attached to said plate support member and capacitance measuring means coupled to said first and second capacitor plates for measuring the change in capacitance between said first capacitor plate and said second capacitor plate as said response element is displaced.

87. A multidimensional force sensor, as described in claim 84, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

88. A multidimensional force sensor, as described in claim 87, wherein said semiconducting material is silicon.

89. A multidimensional force sensor, as described in claim 87, wherein said semiconducting material is germanium.

90. A multidimensional force sensor, as described in claim 84, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

91. A multidimensional force sensor, as described in claim 84, further comprising limiting means partially surrounding said response element for limiting displacement of said response element.

92. A multidimensional force sensor, as described in claim 91, wherein said limiting means comprises a casing.

93. A multidimensional force sensor, as described in claim 84, further comprising limiting means completely surrounding said response element for limiting displacement of said response element.

94. A multidimensional force sensor, as described in claim 84, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

95. A multidimensional force sensor, as described in claim 94, wherein said damping means comprises a fluid.

96. A multidimensional force sensor, as described in claim 84, wherein said sensing means comprises first, second, third and fourth piezoresistors mounted on said first, second, third and fourth beams, respectively.

97. A multidimensional force sensor, as described in claim 96, further comprising first, second, third and fourth reference resistors mounted on said main body, wherein said first and second beams are substantially colinear with each other and substantially perpendicular to said third and fourth beams, wherein said third and fourth beams are substantially colinear with each other and substantially perpendicular to said first and second beams, wherein said first and second piezoresistors comprise a first branch of a first

Wheatstone bridge and said first and second reference resistors comprise a second branch of said first Wheatstone bridge, and wherein said third and fourth piezoresistors comprise a first branch of a second Wheatstone bridge and said third and fourth reference resistors comprise a second branch of said second Wheatstone bridge.

98. A multidimensional force sensor, as described in claim 84, wherein said sensing means comprises:

first, second, third and fourth piezoresistors, mounted on said first, second, third and fourth beams, respectively, extending towards said response element from the first end of each of said first, second, third and fourth beams, along a first side of each of said first, second, third and fourth beams, less than half the distance towards said response element, then extending across each of said first, second, third and fourth beams, and then extending away from said response element along the side of each of said first, second, third and fourth beams opposite from said first side of each of said first, second, third and fourth beams, to the first end of each of said first, second, third and fourth beams.

99. A multidimensional force sensor, comprising:

a substantially planar main body having a first aperture and a second aperture;

a plurality of sensor assemblies extending across said first aperture and said second aperture, each such sensor assembly comprising:

a first beam attached at a first end to an edge of said main body adjacent to said aperture and projecting into said aperture;

a second beam attached at a first end to an edge of said main body adjacent to said aperture and directly opposite said first beam and projecting into said aperture;

a response element attached to the second ends of said first beam and said second beam in said aperture;

first and second piezoresistors, each extending towards said response element from the first end of each of said first and second beams, along a first side of said first and second beams, less than half the distance towards said response element, then extending across said first and second beams, and then extending away from said response element along the side of each of said first and second beams opposite from said first side of said first and second beams, to the first end of each of said first and second beams;

said piezoresistors along the same edge of each of said apertures being electrically connected in series;

said first and second beams in said sensor assemblies in said first aperture being substantially perpendicular to said first and second beams in said sensor assemblies in said second aperture.

100. A multidimensional force sensor, as described in claim 99, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

101. A multidimensional force sensor, as described in claim 100, wherein said semiconducting material is silicon.

102. A multidimensional force sensor, as described in claim 100, wherein said semiconducting material is germanium.

103. A multidimensional force sensor, as described in claim 99, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

104. A multidimensional force sensor, as described in claim 99, further comprising limiting means partially surrounding one of said response elements for limiting displacement of said one response element.

105. A multidimensional force sensor, as described in claim 104, wherein said limiting means comprises a casing.

106. A multidimensional force sensor, as described in claim 99, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

107. A multidimensional force sensor, as described in claim 99, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

108. A multidimensional force sensor, as described in claim 107, wherein said damping means comprises a fluid.

109. A multidimensional force sensor, as described in any one of claims 4 to 7, 22 to 25 or 38 to 41, wherein one of said sensor elements for sensing displacement of one of said beams comprises:

a first sensor component for sensing displacement of said one beam, coupled to said one beam; and

a second sensor component for sensing displacement of said one beam, coupled to said one beam, wherein said second sensor component responds differently from said first sensor component to displacement of said one beam in one direction.

110. A multidimensional force sensor, as described in any one of claims 4, 5, 22, 23, 38, 39, 51, 52, 62, 63, 73 or 74, wherein one of said sensor elements for sensing displacement of one of said beams comprises a piezoresistor mounted on a surface of said one beam.

111. A multidimensional force sensor, as described in any one of claims 4, 5, 22, 23, 38, 39, 51, 52, 62, 63, 73 or 74, wherein one of said sensor elements for sensing displacement of one of said beams comprises a piezoresistor embedded in the longitudinal axis of said one beam for sensing stress in said one beam.

112. A multidimensional force sensor, as described in any one of claims 6, 7, 24, 25, 40, 41, 52, 63 or 74, further comprising a plate support member attached to said main body and extending towards one of said response elements, and wherein said sensor element coupled to said beam attached to said one response element comprises:

a first capacitor plate mounted on said one response element;

a second capacitor plate mounted on said plate support member in close proximity and substantially parallel to said first capacitor plate; and

capacitance measuring means coupled to said first and second capacitor plates for measuring the change in capacitance between said first capacitor plate and said second capacitor plate as said one response element is displaced.

113. A multidimensional force sensor, as described in Claim 112, wherein each of said first and second capacitor plates comprises a plurality of electrically conductive strips parallel to each other and electrically connected to each other.

114. A multidimensional force sensor, as described in Claim 112, wherein said capacitor plates are substantially rectangular.

115. A multidimensional force sensor, as described in claim 112, wherein said first capacitor plate and said second capacitor plate only partially overlap.

116. A multidimensional force sensor, as described in claim 112, wherein said first capacitor plate is of a different shape from said second capacitor plate.

117. A multidimensional force sensor, as described in Claim 116, wherein each of said first and second capacitor plates comprises a plurality of electrically conductive strips parallel to each other and electrically connected to each other, and each of said

first and second capacitor plates only partially overlaps the other.

118. A multidimensional force sensor, as described in Claim 116, wherein said first capacitor plate is substantially triangular in shape, wherein said second capacitor plate is substantially rectangular in shape, and wherein only a portion of said first capacitor plate overlaps said second capacitor plate.

119. A multidimensional force sensor, as described in Claim 118, wherein each of said first and second capacitor plates comprises a plurality of electrically conductive strips parallel to each other and electrically connected to each other.

120. A multidimensional force sensor, as described in any one of claims 6, 7, 24, 25, 40, 41, 52, 63 or 74, further comprising a plate support member attached to said main body and extending towards one of said response elements, and wherein said sensor element coupled to said beam attached to said one response element comprises:

a first capacitor plate mounted on said plate support member in close proximity to said one response element and offset to one side of said one response element;

a second capacitor plate mounted on said plate support member in close proximity to said one response element, substantially parallel to said first capacitor plate, and offset to the opposite side of said one response element from said first capacitor plate;

a third capacitor plate mounted on said one response element, substantially parallel to said first capacitor plate and said second capacitor plate, and partially overlapping said first capacitor plate and said second capacitor plate; and

capacitance measuring means coupled to said first, second and third capacitor plates for measuring the change in capacitance between said first capacitor plate and said third capacitor plate and between said

second capacitor plate and said third capacitor plate as said one response element is displaced.

121. A multidimensional force sensor, as described in Claim 120, wherein each of said first, second and third capacitor plates comprises a plurality of electrically conductive strips parallel to each other and electrically connected to each other.

122. A multidimensional force sensor, as described in claim 120, further comprising:

piezoresistor means embedded in the longitudinal axis of said beam for sensing stress in said beam.

123. A multidimensional force sensor, as described in any one of claims 6, 7, 24, 25, 40, 41, 52, 63 or 74, further comprising a plate support member attached to said main body and extending towards one of said response elements, and wherein said sensor element coupled to said beam attached to said one response element comprises:

a first capacitor plate mounted on said plate support member in close proximity to said one response element and offset to one side of said one response element;

a second capacitor plate mounted on said plate support member adjacent to said first capacitor plate, substantially parallel to said first capacitor plate, and having its center in close proximity to said one response element;

a third capacitor plate mounted on said plate support member in close proximity to said one response element, substantially parallel to said first capacitor plate and said second capacitor plate, and offset to the opposite side of said one response element from said first capacitor plate;

a fourth capacitor plate that is substantially larger than said second capacitor plate mounted on said one response element, substantially parallel to said first capacitor plate, said second capacitor plate and said third capacitor plate, centered over and completely

overlapping said second capacitor plate and partially overlapping said first capacitor plate and said third capacitor plate; and

capacitance measuring means coupled to said first, second, third and fourth capacitor plates for measuring the change in capacitance between said first capacitor plate and said fourth capacitor plate, between said second capacitor plate and said fourth capacitor plate, and between said third capacitor plate and said fourth capacitor plate, as said one response element is displaced.

124. A multidimensional force sensor, as described in Claim 123, wherein each of said first, second, third and fourth capacitor plates comprises a plurality of electrically conductive strips parallel to each other and electrically connected to each other.

125. A multidimensional force sensor, as described in claim 123, further comprising:

piezoresistor means embedded in the longitudinal axis of said beam for sensing stress in said beam.

126. A multidimensional force sensor, as described in any one of claims 2, 20, 36, 52, 63, or 74, wherein one of said response elements comprises a mass.

127. A multidimensional force sensor, as described in any one of claims 2, 20, 36, 52, 63, or 74, wherein one of said response elements comprises a material responsive to a magnetic field.

128. A multidimensional force sensor, as described in any one of claims 2, 20, 36, 52, 63, or 74, wherein one of said response elements comprises a material responsive to an electric field.

129. A multidimensional force sensor, as described in any one of claims 2, 20, 36, 52, 63, or 74, wherein one of said response elements comprises an electrically charged material.

130. A multidimensional force sensor, as described in any one of claims 2, 20, 36, 52, 63, or 74, wherein

one of said response elements comprises a magnetized material.

131. A multidimensional force sensor, comprising:

a main body;

a plurality of beams, each having a first end and a second end, said beams mechanically coupled at their first ends to said main body, said plurality of beams arranged in a three dimensional array; and

sensor means, coupled to each of said plurality of beams, for sensing displacement of each of said beams.

132. A multidimensional force sensor, as described in claim 131, further comprising:

a plurality of response elements, each attached to the second end of a single beam.

133. A multidimensional force sensor, as described in claim 132, wherein said main body is substantially planar.

134. A multidimensional force sensor, as described in claim 133, wherein said sensing means comprises a plurality of discrete electromechanical sensor elements, each sensor element producing an electrical signal in response to displacement of a single corresponding beam.

135. A multidimensional force sensor, as described in claim 134, wherein said plurality of sensor elements are mounted on corresponding ones of said plurality of beams.

136. A multidimensional force sensor, as described in claim 135, wherein said main body and said beams comprise an integrally formed piece of semiconducting material.

137. A multidimensional force sensor, as described in claim 136, wherein said semiconducting material is silicon.

138. A multidimensional force sensor, as described in claim 136, wherein said semiconducting material is germanium.

139. A multidimensional force sensor, as described in claim 135, wherein said main body and said beams comprise an integrally formed piece of material selected from the group consisting of quartz, glass and ceramics.

140. A multidimensional force sensor, as described in claim 132, further comprising limiting means partially surrounding one of said response elements, for limiting displacement of said one response element.

141. A multidimensional force sensor, as described in claim 140, wherein said limiting means comprises a casing.

142. A multidimensional force sensor, as described in claim 132, further comprising limiting means completely surrounding one of said response elements for limiting displacement of said one response element.

143. A multidimensional force sensor, as described in claim 132, further comprising damping means surrounding one of said beams, for damping vibration of said one beam.

144. A multidimensional force sensor, as described in claim 143, wherein said damping means comprises a fluid.

145. A multidimensional force sensor, as described in claim 132, wherein each of said beams is constructed so that displacement of each of said beams is substantially anisotropic with respect to force.

146. A multidimensional force sensor, as described in claim 145, wherein each of said beams is so constructed that each of said beams is substantially displaceable by a force in only one dimension and said dimension is different for each of said beams.

147. A sensor for sensing displacement of a response element attached to a main body, comprising:

a plate holding member attached to said main body and extending towards said response element;

a first set of electrically conductive strips electrically connected to each other mounted on said response element;

a second set of electrically conductive strips electrically connected to each other mounted on said plate holding member in close proximity and substantially parallel to said first set of electrically conductive strips; and

capacitance measuring means, coupled to said first set of electrically conductive strips and said second set of electrically conductive strips, for measuring the change in capacitance between said first set of electrically conductive strips and said second set of electrically conductive strips as said response element is displaced.

148. A sensor for sensing displacement of a beam attached to a main body at a first end and having a response element attached to a second end of said beam, said displacement being caused by a force applied to said response element, comprising:

a plate holding member attached to said main body and extending towards said response element;

a first capacitor plate attached to said response element;

a second capacitor plate having a different shape from said first capacitor plate attached to said plate holding member and only partially overlapping said first capacitor plate substantially parallel to and in close proximity to said first capacitor plate; and

capacitance measuring means, coupled to said first capacitor plate and said second capacitor plate, for measuring the change in capacitance between said first capacitor plate and said second capacitor plate as said response element is displaced by said force.

149. A sensor for sensing displacement of a response element attached to a main body, comprising:

a plate holding member attached to said main body and extending towards said response element;

a first triangular capacitor plate mounted on said response element;

a second rectangular capacitor plate mounted on said plate holding member in close proximity and substantially parallel to said first capacitor plate; and

capacitance measuring means coupled to said first triangular capacitor plate and said second rectangular capacitor plate for measuring the change in capacitance between said first triangular capacitor plate and said second rectangular capacitor plate as said response element is displaced.

150. A sensor for sensing displacement of a response element attached to a main body, as described in claim 149, wherein each of said first triangular capacitor plate and said second rectangular capacitor plate comprises a plurality of electrically conductive strips, parallel to each other and electrically connected to each other.

151. A sensor for sensing displacement of a response element attached to a main body, comprising:

a plate holding member attached to said main body and extending towards said response element;

a first capacitor plate mounted on said plate holding member in close proximity to said response element;

a second capacitor plate mounted on said plate holding member in close proximity to said response element, parallel to said first capacitor plate, and offset to the opposite side of said beam from said first capacitor plate;

a third capacitor plate mounted on said response element, parallel to said first capacitor plate and said second capacitor plate, and partially overlapping said first capacitor plate and said second capacitor plate; and

capacitance measuring means, coupled to said first, second and third capacitor plates, for measuring the change in capacitance between said first capacitor

plate and said third capacitor plate and between said second capacitor plate and said third capacitor plate as said response element is displaced.

152. A sensor for sensing displacement of a response element attached to a main body, as described in claim 151, wherein said capacitance measuring means comprises:

a first capacitance measuring means coupled to said first and third capacitor plates for measuring the change in capacitance between said first and third capacitor plates as said response element is displaced; and

a second capacitance measuring means coupled to said second and third capacitor plates for measuring the change in capacitance between said second and third capacitor plates as said response element is displaced.

153. A sensor for sensing displacement of a response element attached to a main body, as described in claim 151, wherein each of said first, second and third capacitor plates comprises a plurality of electrically conductive strips, parallel to each other and electrically connected to each other.

154. A sensor for sensing displacement of a response element attached to a main body, as described in claim 151, further comprising:

piezoresistor means embedded in the longitudinal axis of said beam for sensing stress in said beam.

155. A sensor for sensing displacement of a response element attached to a main body, comprising:

a plate holding member attached to said main body and extending towards said response element;

a first capacitor plate mounted on said plate holding member in close proximity to said response element;

a second capacitor plate mounted on said plate holding member adjacent to said first capacitor plate, substantially parallel to said first capacitor plate, and

having its center in close proximity to said response element;

a third capacitor plate mounted on said plate holding member in close proximity to said response element, substantially parallel to said first capacitor plate and said second capacitor plate, and offset to the opposite side of said response element from said first capacitor plate;

a fourth capacitor plate that is substantially larger than said second capacitor plate mounted on said response element, substantially parallel to said first capacitor plate, said second capacitor plate and said third capacitor plate, centered over and completely overlapping said second capacitor plate and partially overlapping said first capacitor plate and said third capacitor plate; and

capacitance measuring means, coupled to said first, second, third and fourth capacitor plates, for measuring the change in capacitance between said first and fourth capacitor plates, between said second and fourth capacitor plates, and between said third and fourth capacitor plates, as said response element is displaced.

156. A sensor for sensing displacement of a response element attached to a main body, as described in claim 155, wherein said capacitance measuring means comprises:

a first capacitance measuring means coupled to said first and fourth capacitor plates for measuring the change in capacitance between said first and fourth capacitor plates as said response element is displaced;

a second capacitance measuring means coupled to said second and fourth capacitor plates for measuring the change in capacitance between said second and fourth capacitor plates as said response element is displaced; and

a third capacitance measuring means coupled to said third and fourth capacitor plates for measuring the

change in capacitance between said third and fourth capacitor plates as said response element is displaced.

157. A sensor for sensing displacement of a response element attached to a main body, as described in claim 155, wherein each of said first, second, third and fourth capacitor plates comprises a plurality of electrically conductive strips, parallel to each other and electrically connected to each other.

158. A sensor for sensing displacement of a response element attached to a main body, as described in claim 155, further comprising:

piezoresistor means embedded in the longitudinal axis of said beam for sensing stress in said beam.

159. A process for sensing a multidimensional quantity with reduced measurement error, comprising:

selecting a plurality of sensor elements, each of which responds to a minimal number of dimensional components of the quantity being measured;

arranging said plurality of sensor elements in an array;

stimulating said sensor array with said quantity;

sensing the components of said quantity with said sensor elements and producing output signals from said sensor elements responsive to the magnitudes of said sensed dimensional components; and

generating a multidimensional description of said quantity in response to said output signals.

160. A process for sensing a multidimensional quantity with reduced measurement error, as described in claim 159, further comprising:

selecting said sensor elements for maximum sensitivity to one dimension of said quantity and minimum sensitivity to all other dimensions of said quantity.

161. A process for sensing the direction and magnitude of a plurality of applied forces with reduced measurement error, comprising:

selecting a plurality of force sensor elements, each of which responds to a minimal number of components of said applied forces;

arranging said plurality of force sensor elements in an array;

predetermining different components of said applied forces to which said plurality of force sensor elements responds;

stimulating said sensor array with said applied forces;

sensing components of said applied forces with said force sensor elements and producing output signals from said force sensor elements; and

generating a description of the direction and magnitude of all components of said applied forces in response to said output signals.

162. A process for sensing the direction and magnitude of a plurality of applied forces with reduced measurement error, as described in claim 161, further comprising selecting force sensor elements having maximum sensitivity to one component of said applied forces and minimum sensitivity to all other components of said applied forces.

163. A process for sensing the direction and magnitude of a plurality of applied forces with reduced measurement error, as described in claim 161, wherein:

each of said force sensor elements senses the magnitude of the force component it responds to and produces said output signal in response to said sensed magnitude; and

said generating step comprises generating a description of the direction and magnitude of a plurality of components of said applied forces in response to said output signals.

164. A multidimensional force sensor, as described in claim 22, wherein one of said beams comprises a piezoresistive material, whereby said one

beam comprises a sensor element for sensing displacement of said one beam.

165. A sensor for sensing displacement of a response element attached to a main body, as described in any one of claims 147 to 158, wherein said plate holding member comprises a substrate attached to said main body.

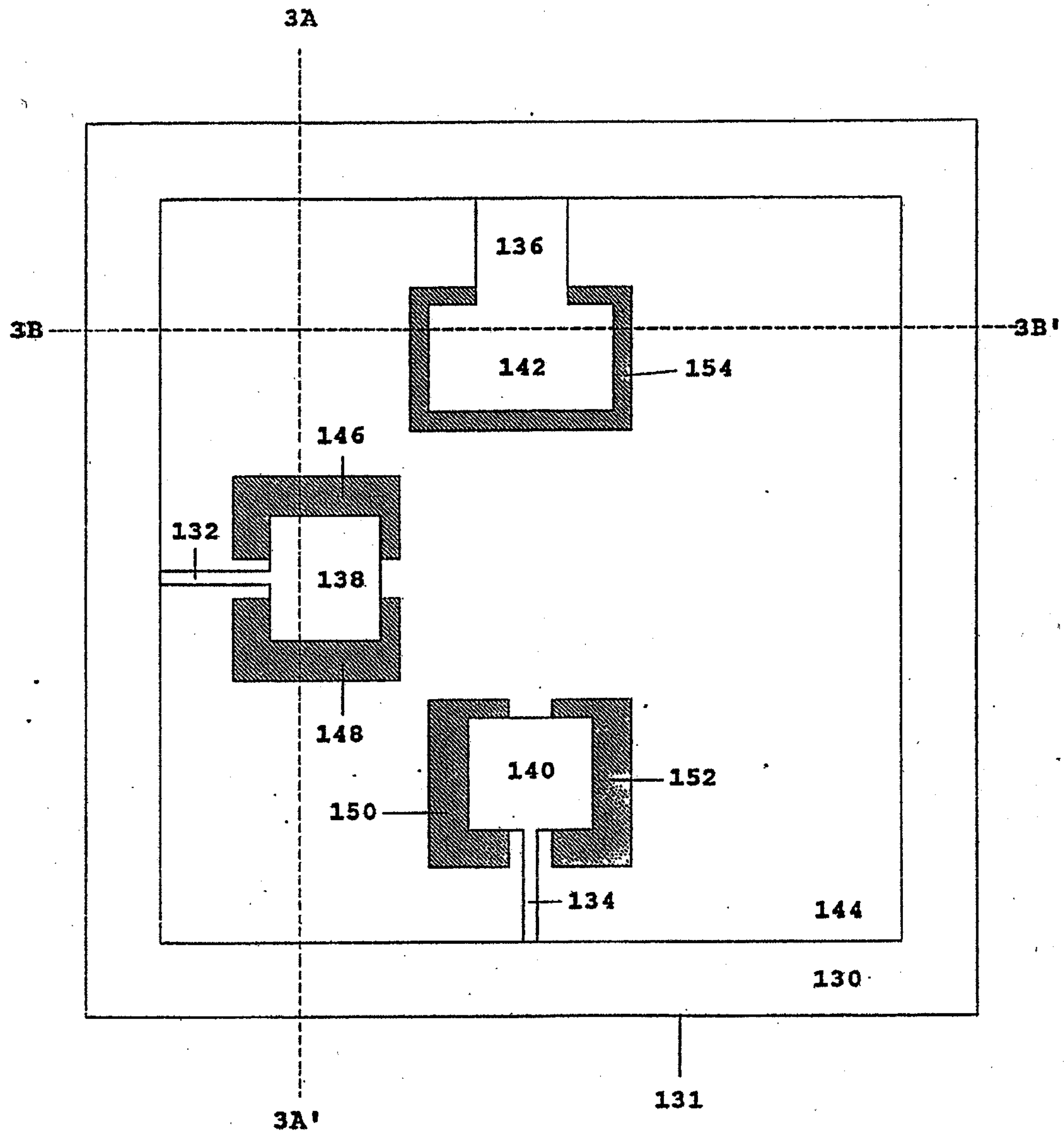

3A
136
3B
3B'
142
154
146
132
138
148
140
152
150
134
144
130
131
3A'

FIG. 1

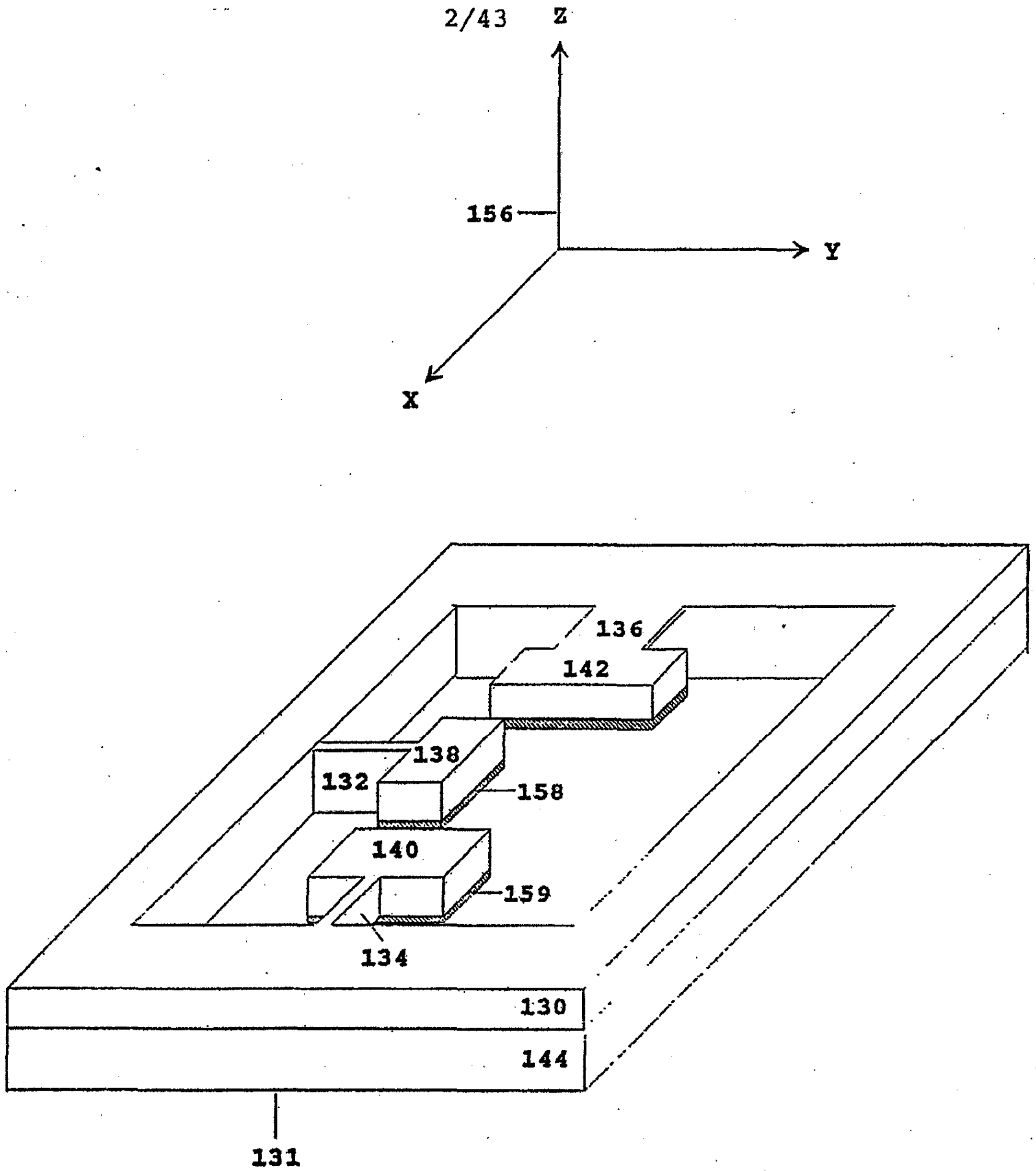
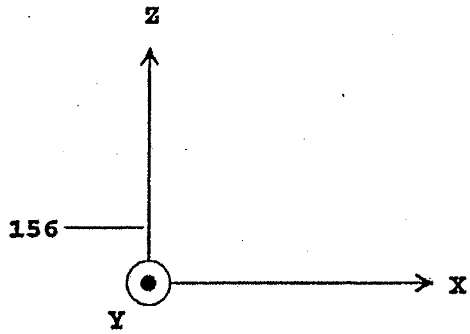


FIG. 2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156
X
Y

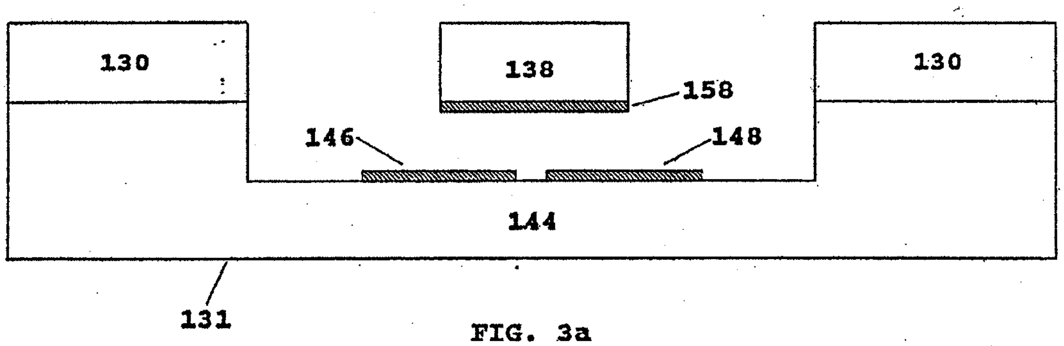
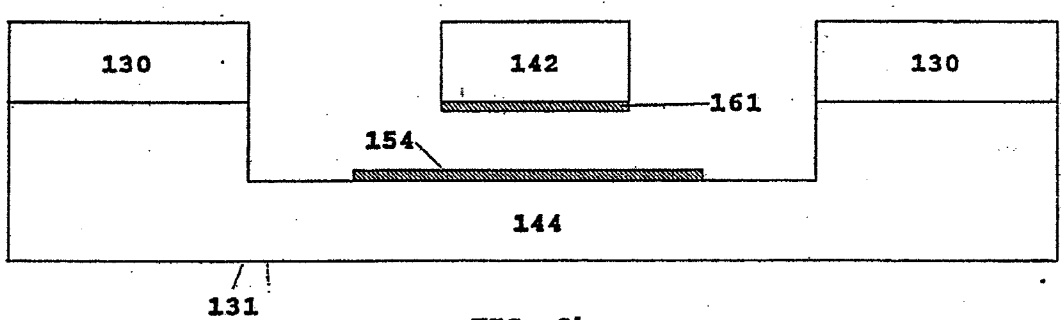

130
138
130
158
146
148
144
131

FIG. 3a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130
161
154
144
131

FIG. 3b

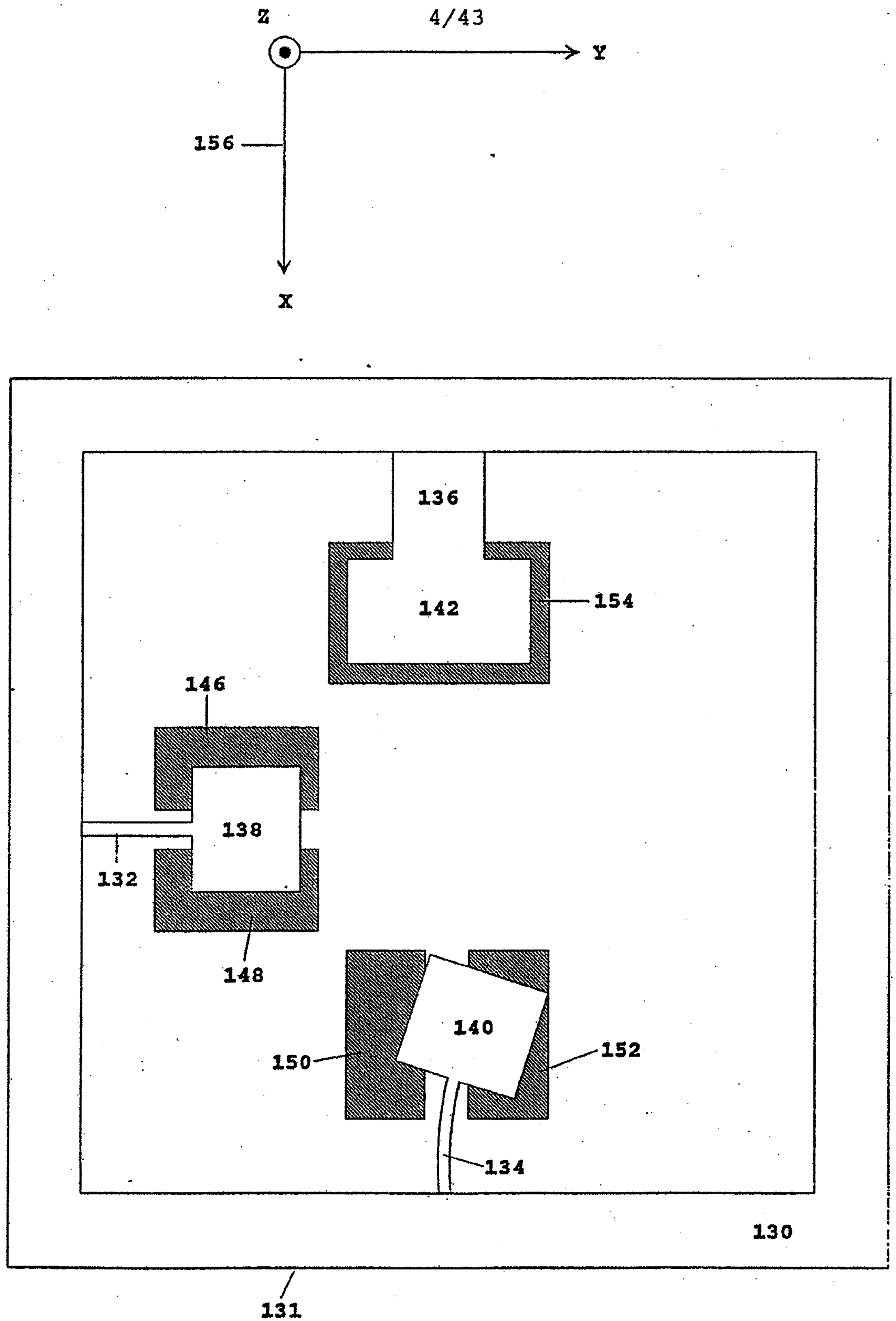

FIG. 4

SUBSTITUTE SHEET

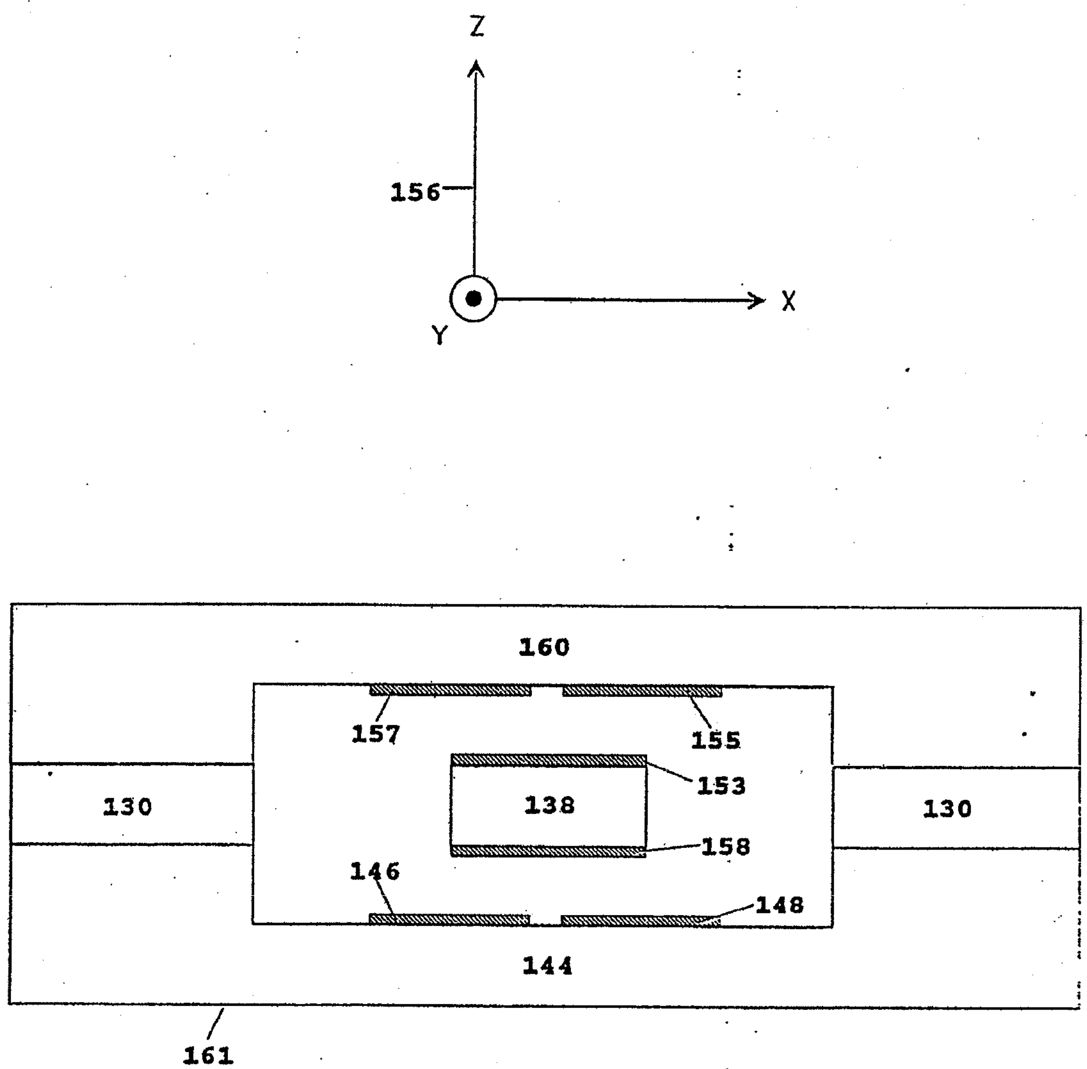

FIG. 5

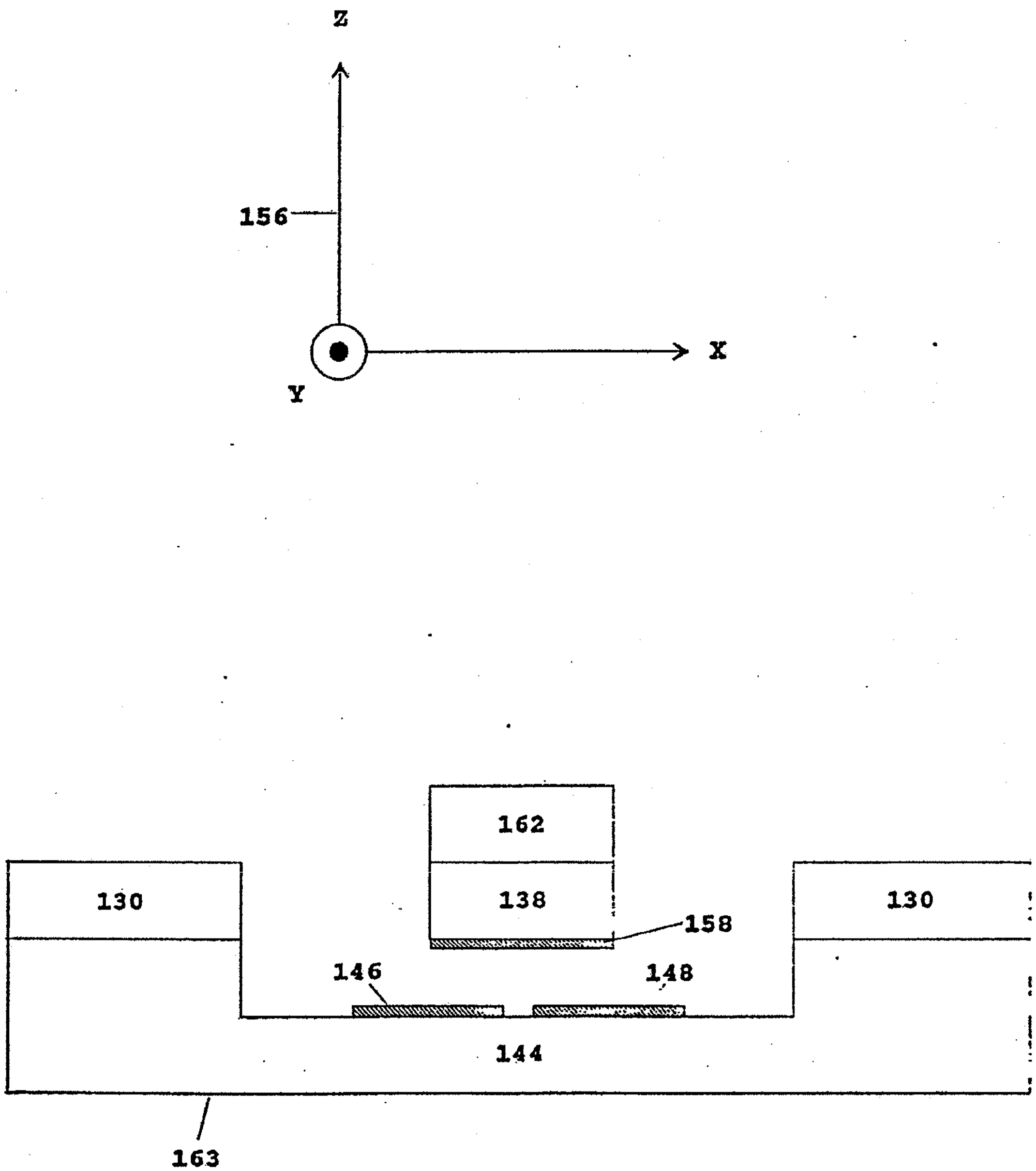

FIG. 6

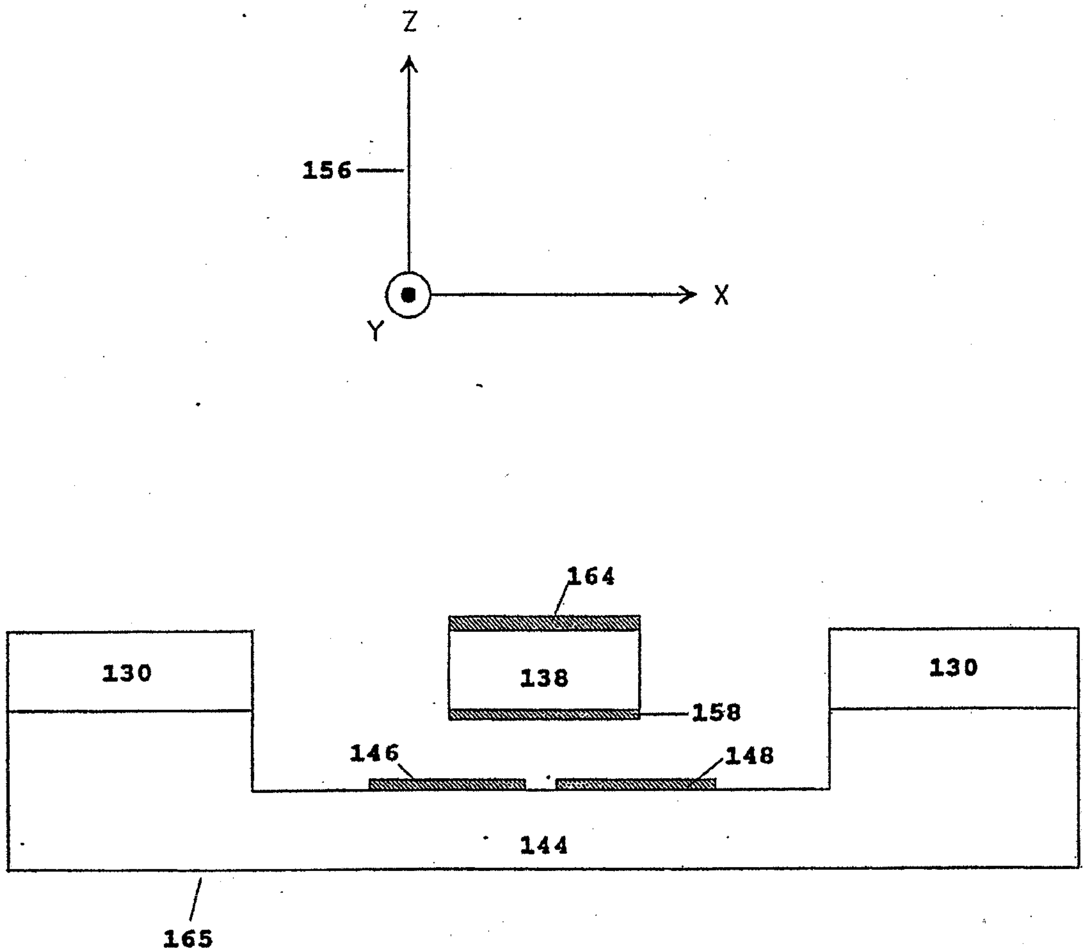

Fig. 7

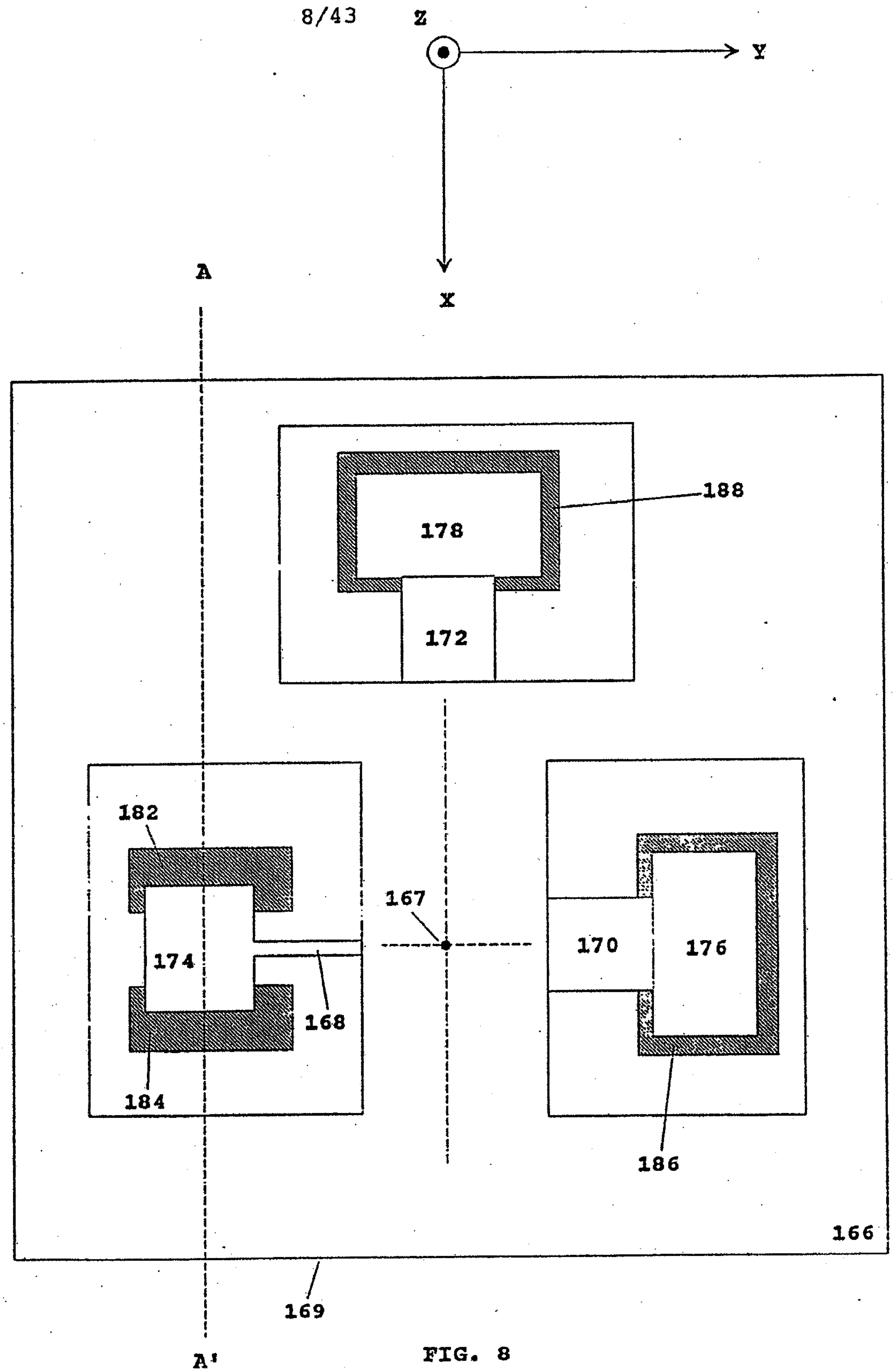

FIG. 8

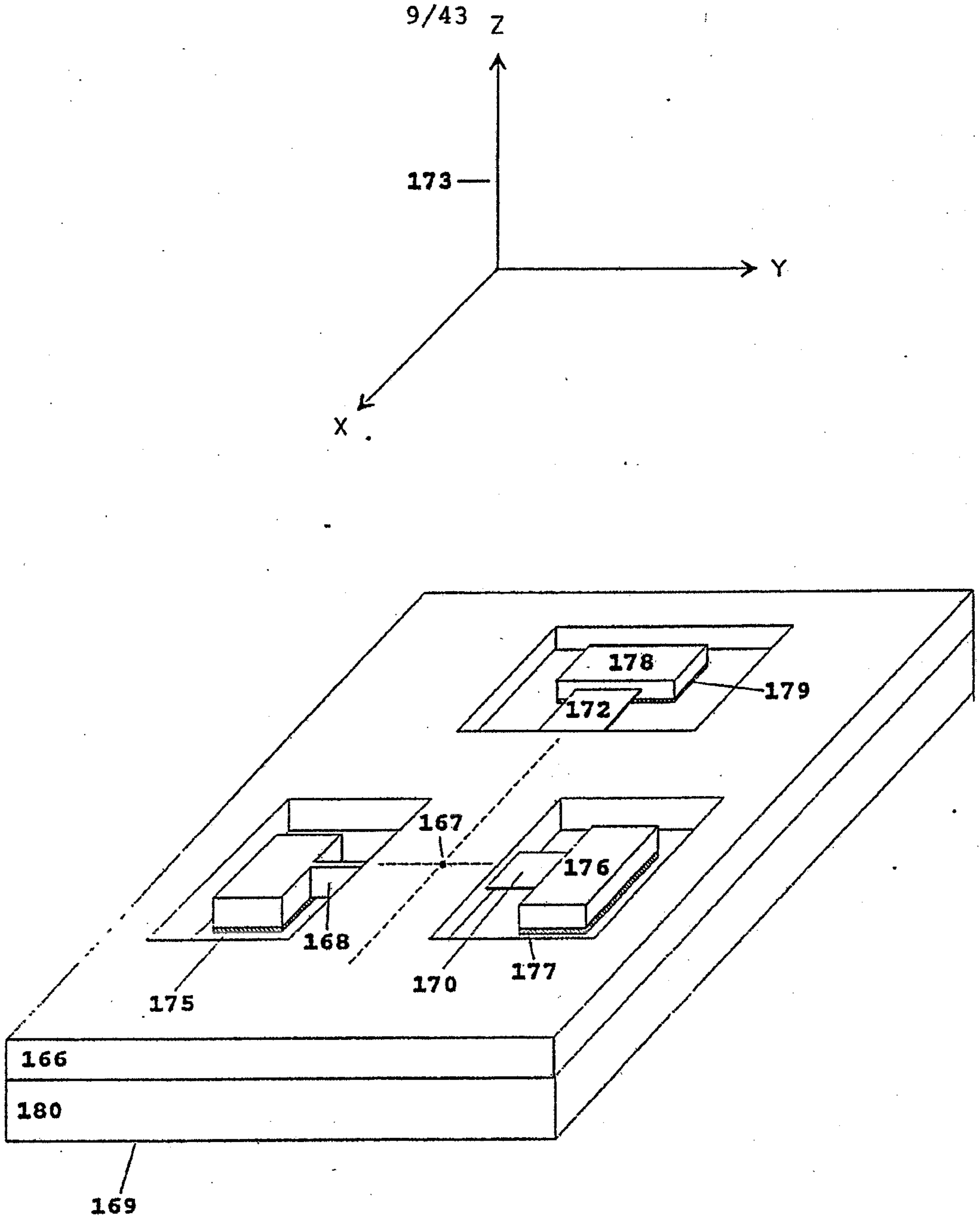

FIG. 9

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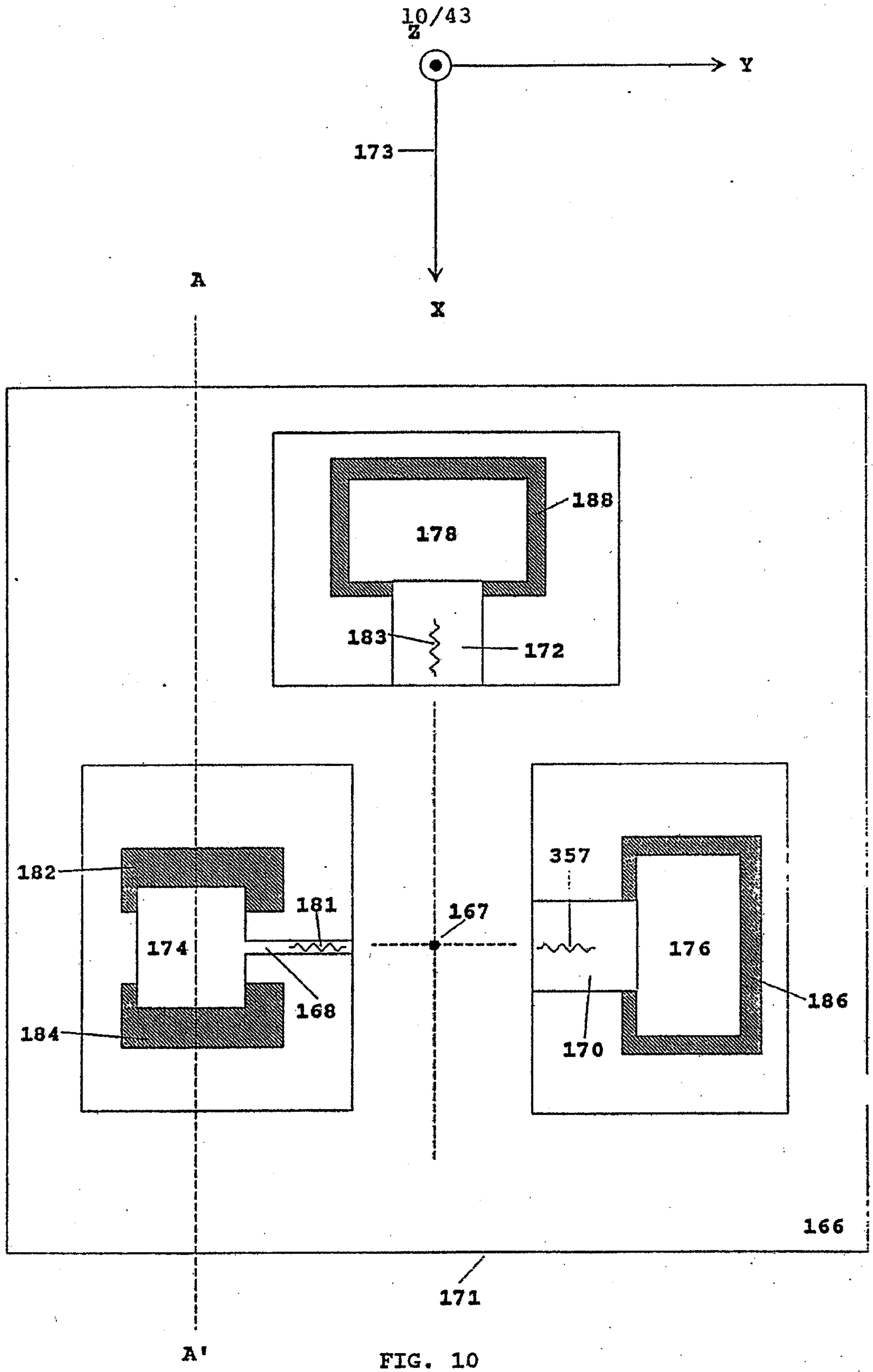

FIG. 10

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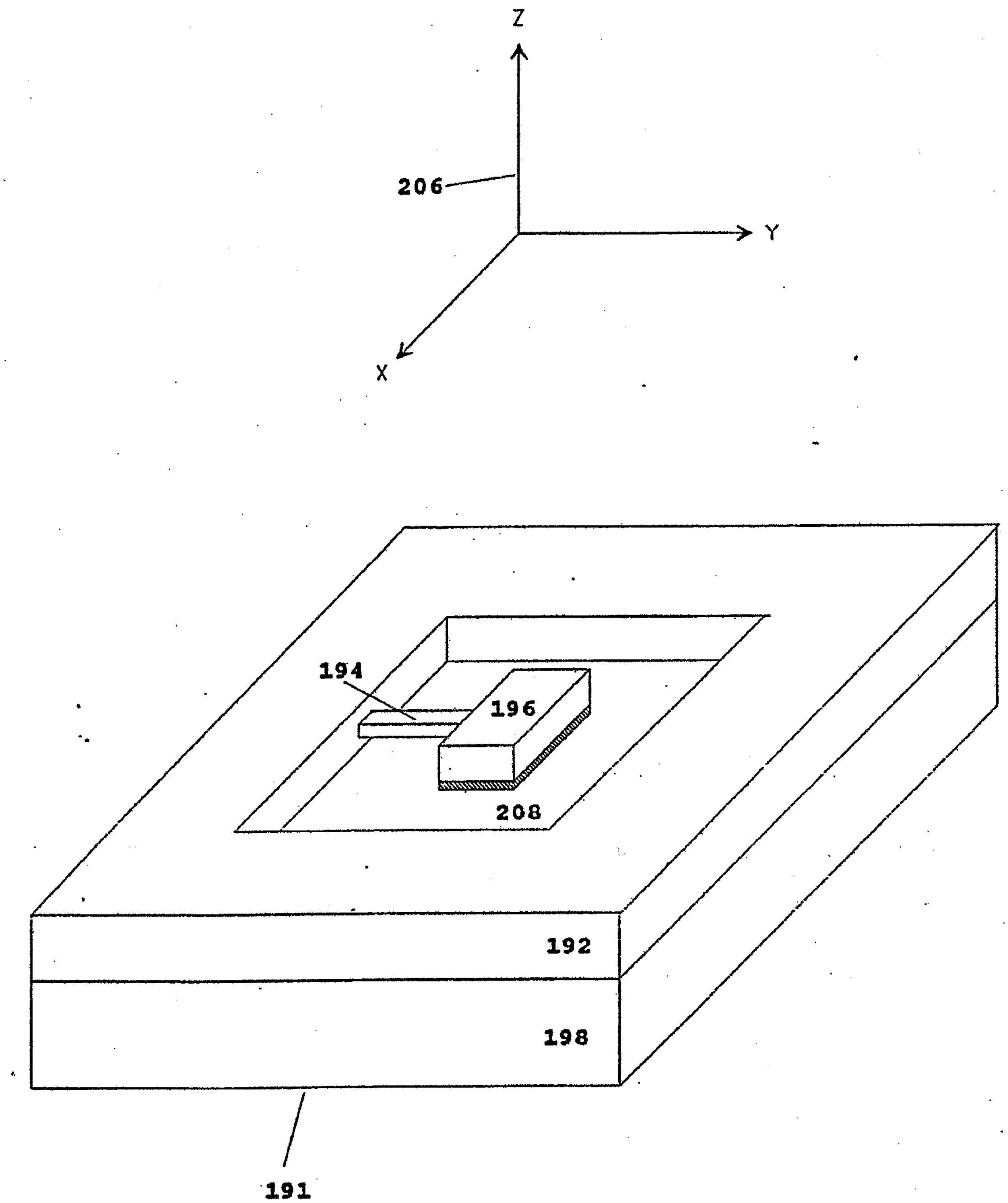

FIG. 11

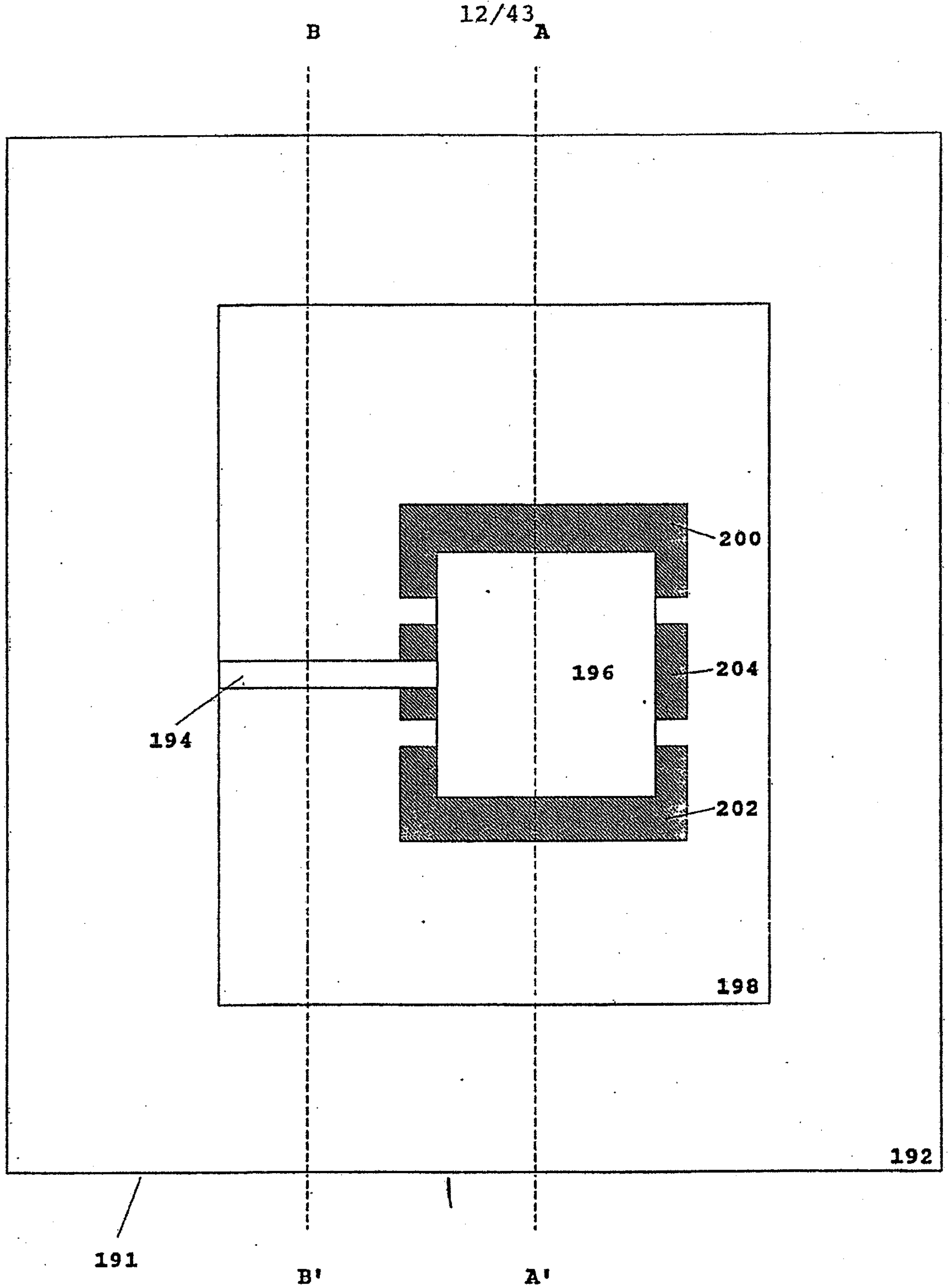

FIG. 12

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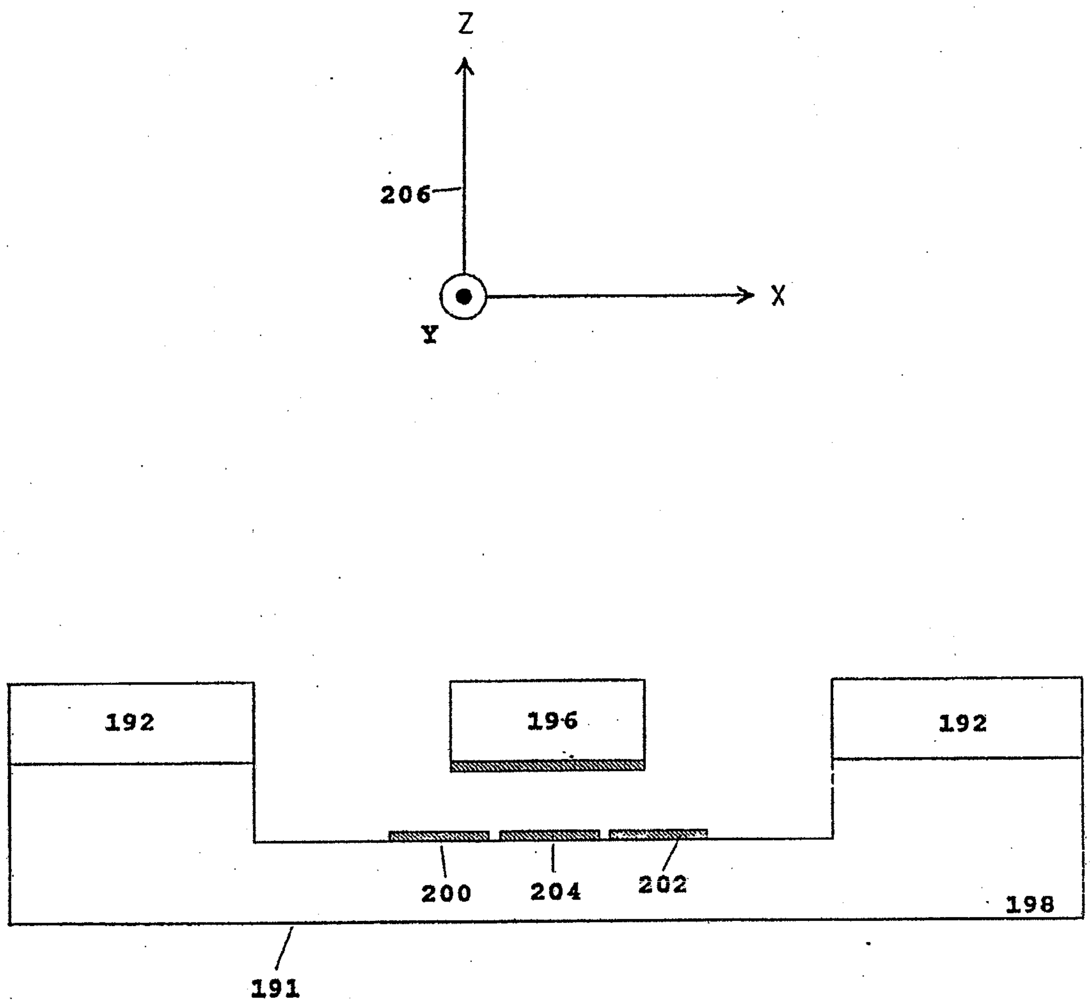

FIG. 13

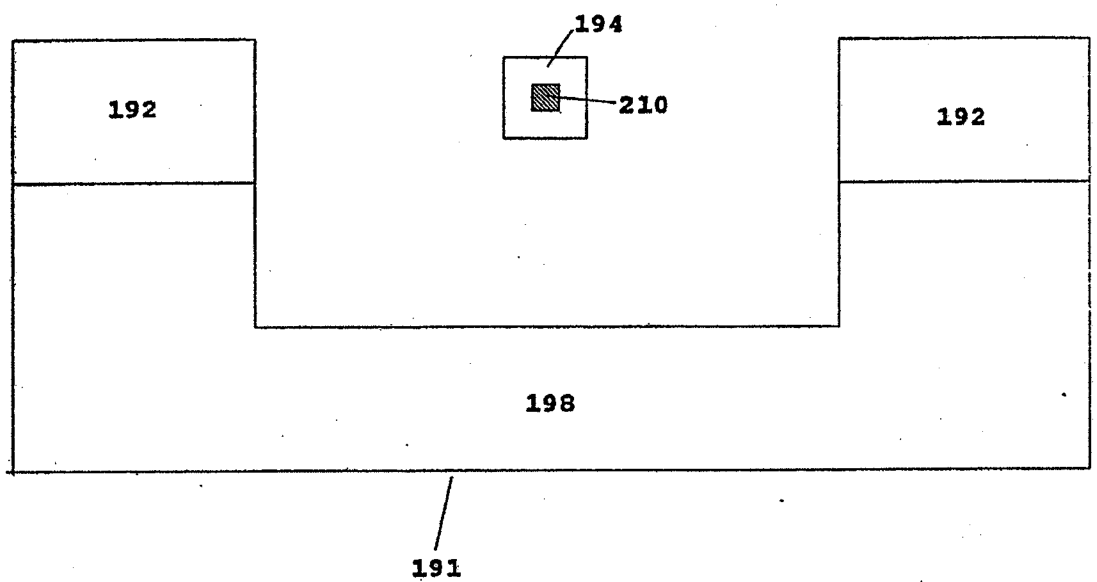

FIG. 14

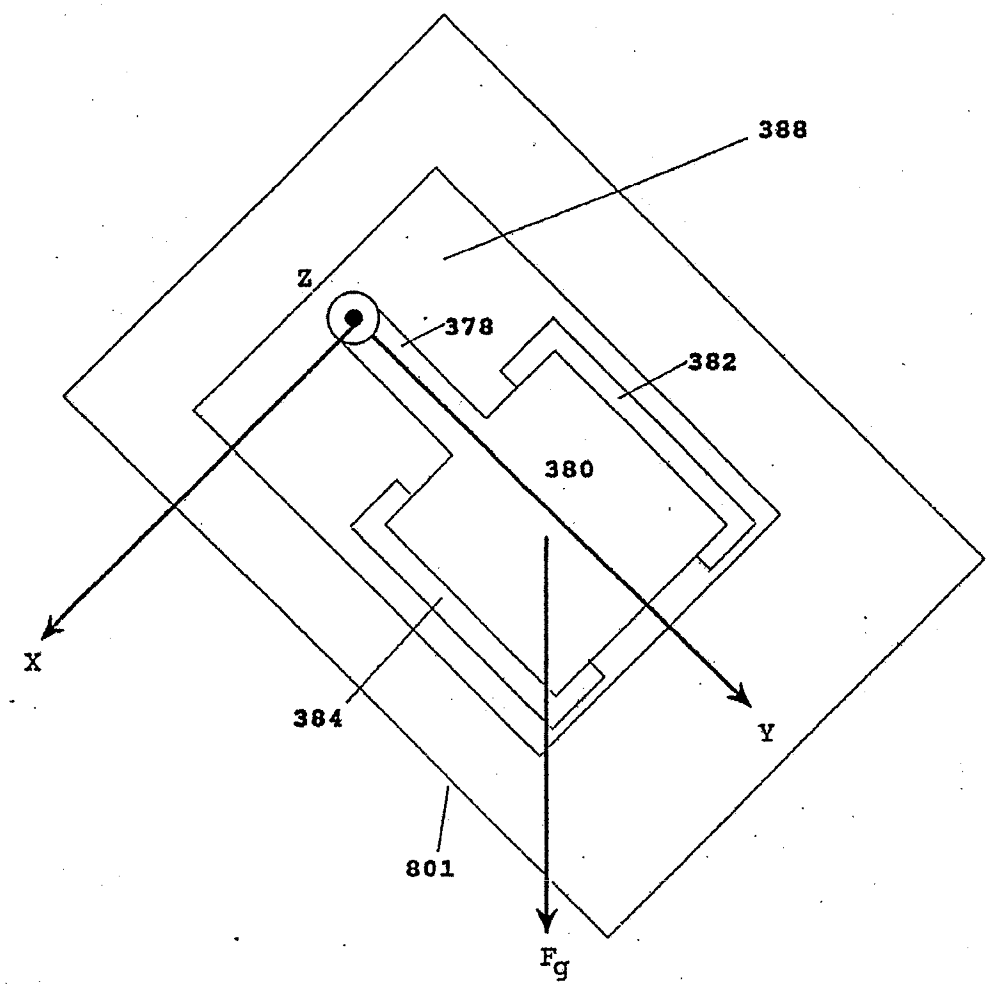

FIG. 15

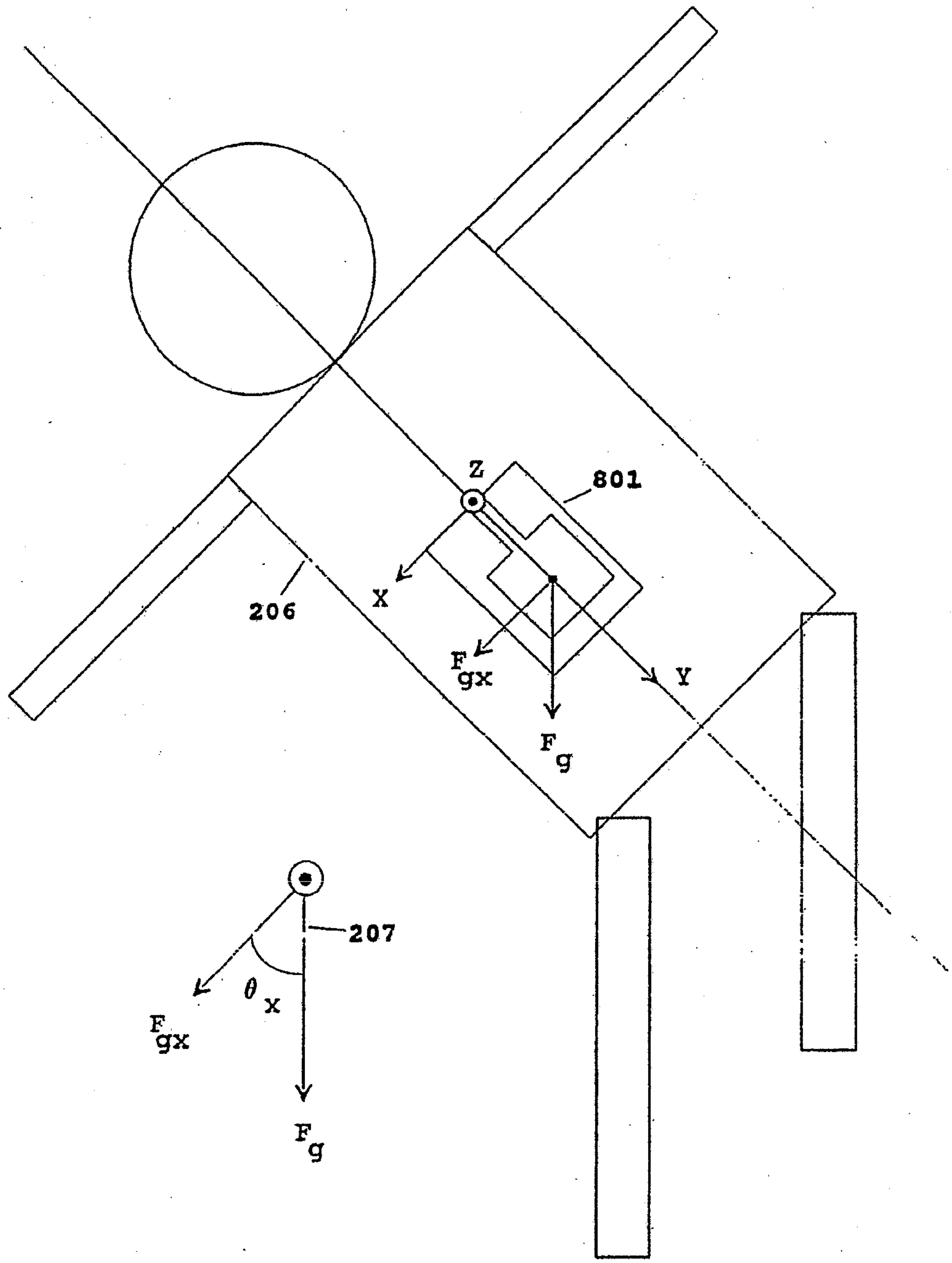

FIG. 16

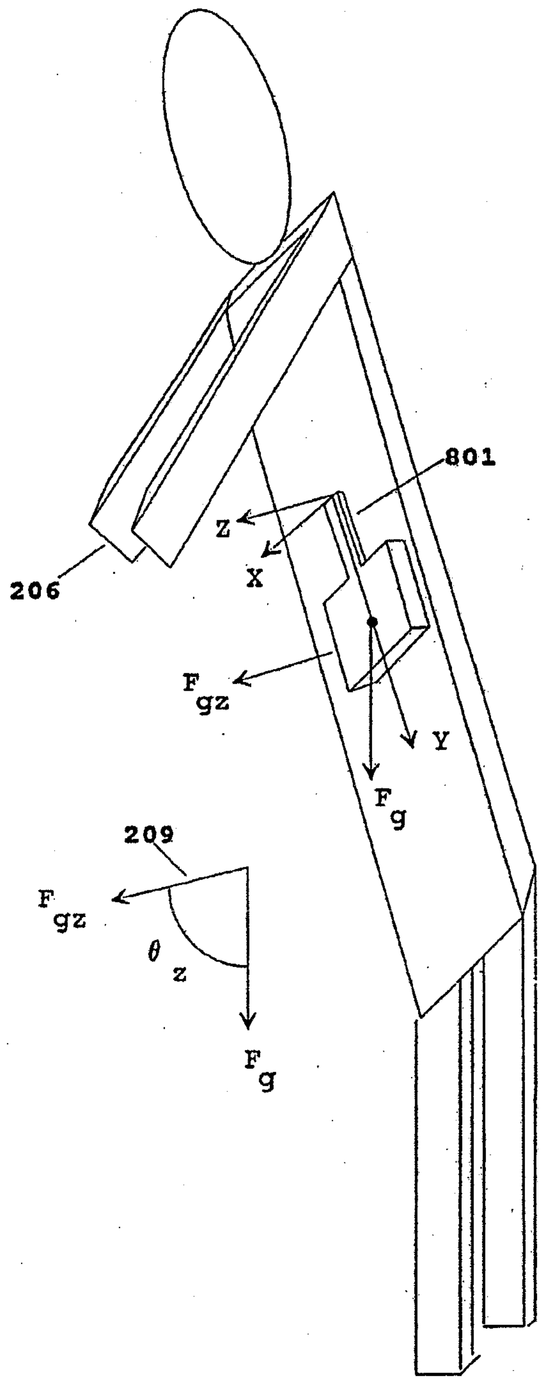

FIG. 17

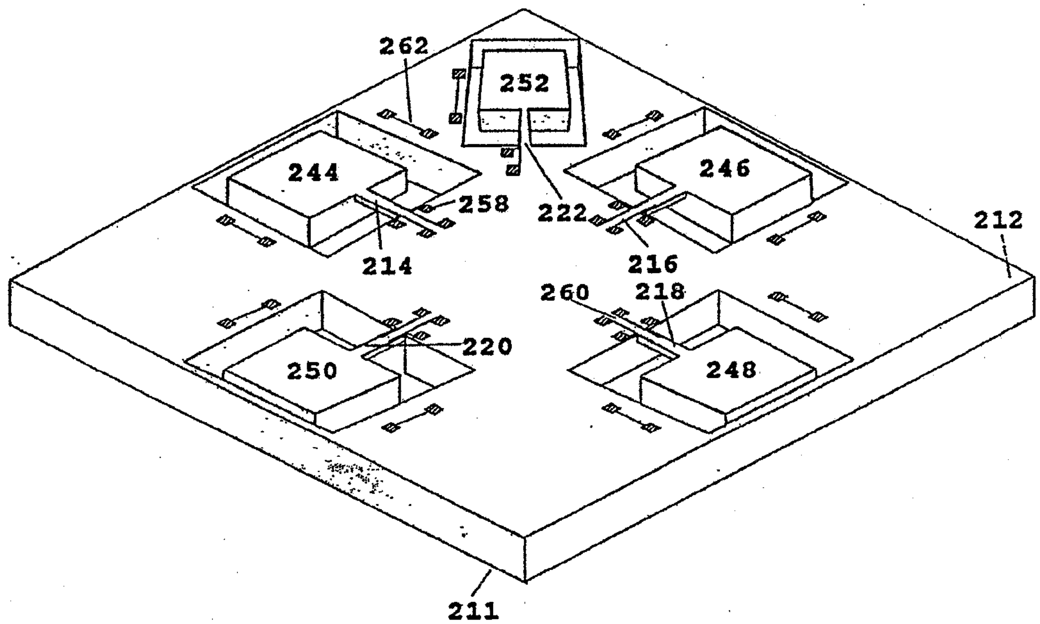

FIG. 18

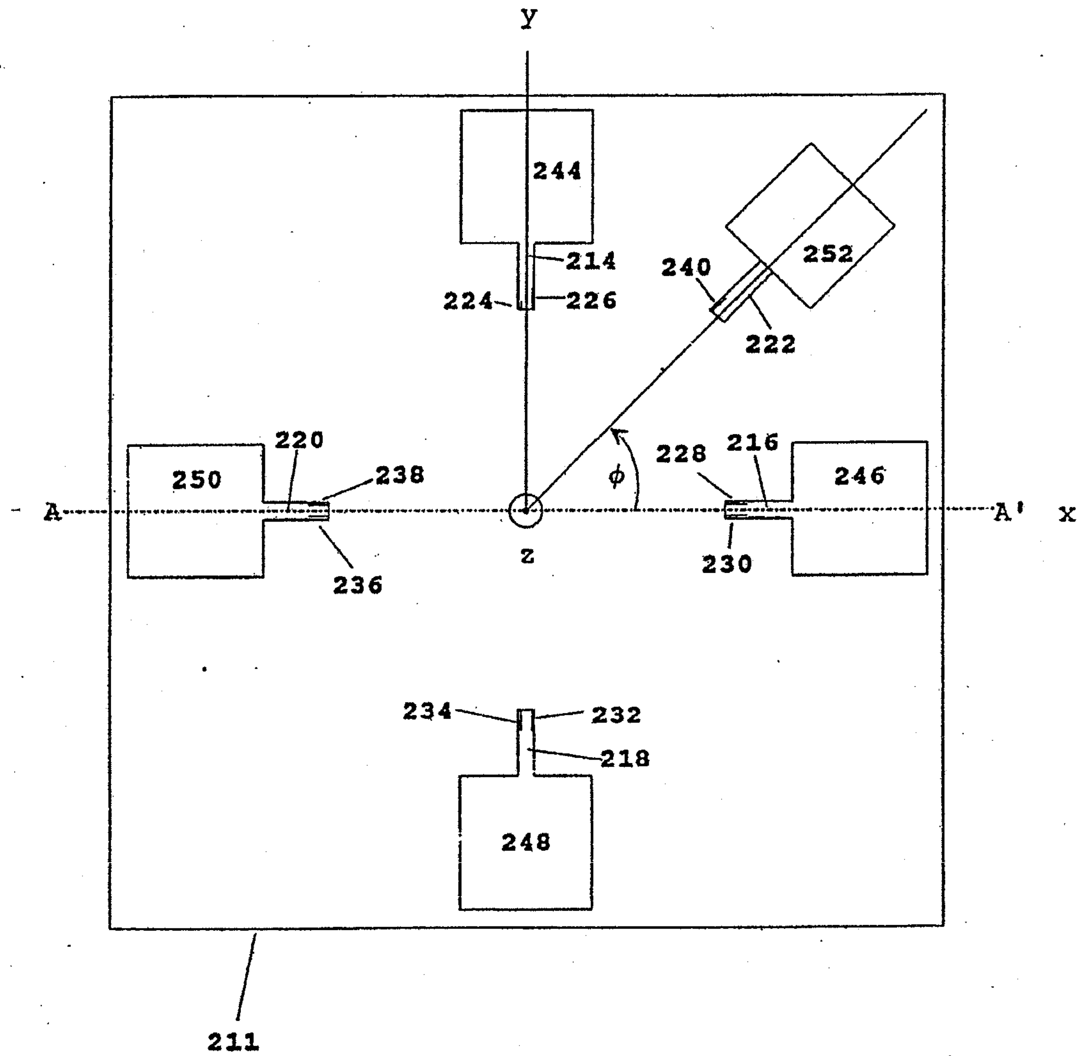
y
244
214
224
226
240
252
222
250
220
238
228
216
246
A
A'
x
z
ϕ
236
230
234
232
218
248
211

FIG. 19

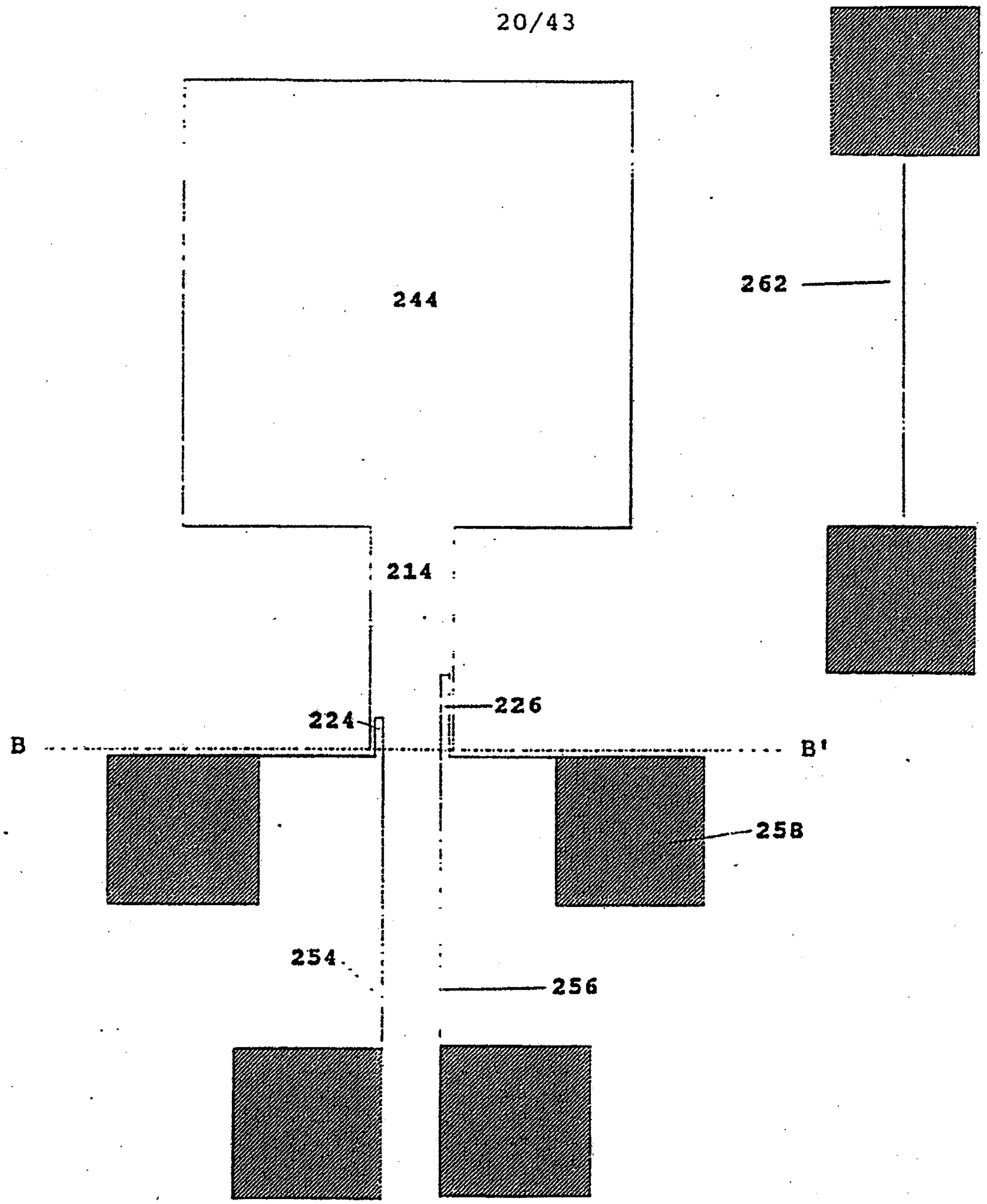

FIG. 20

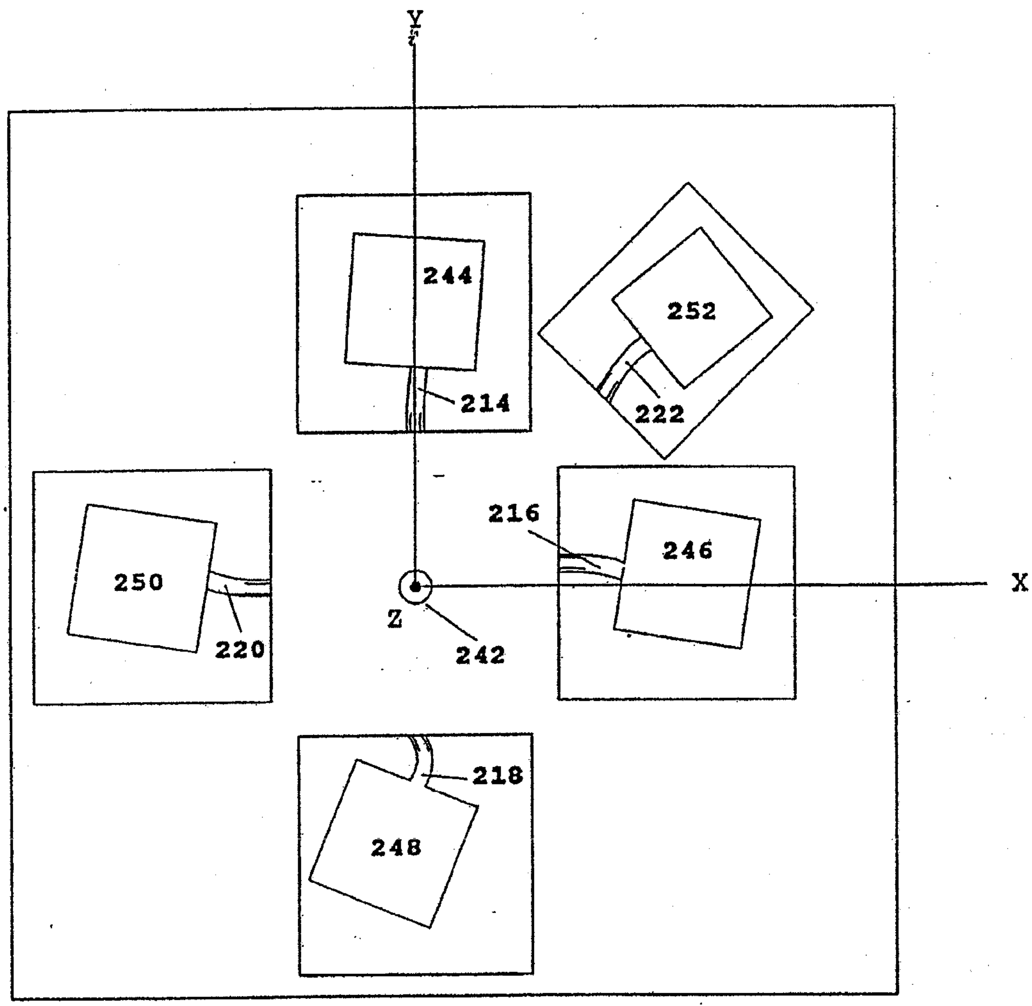

FIG. 21

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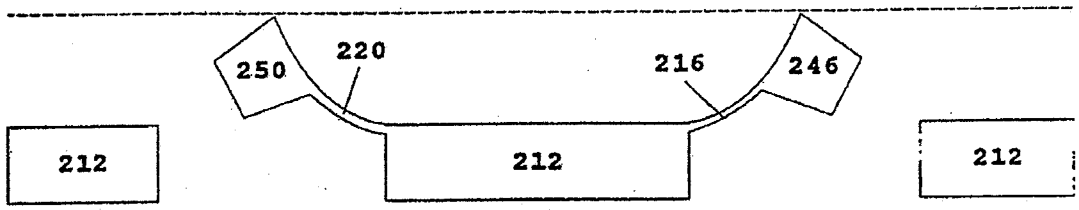

FIG. 22a

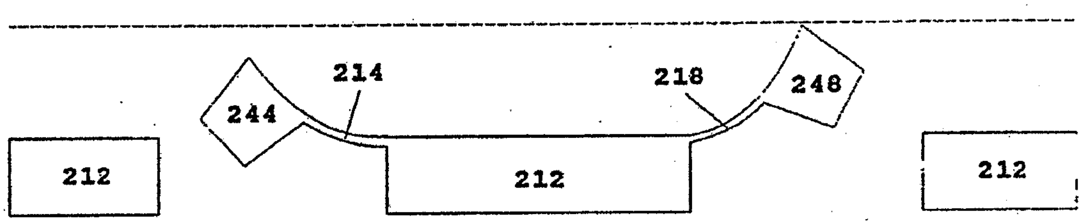

FIG. 22b

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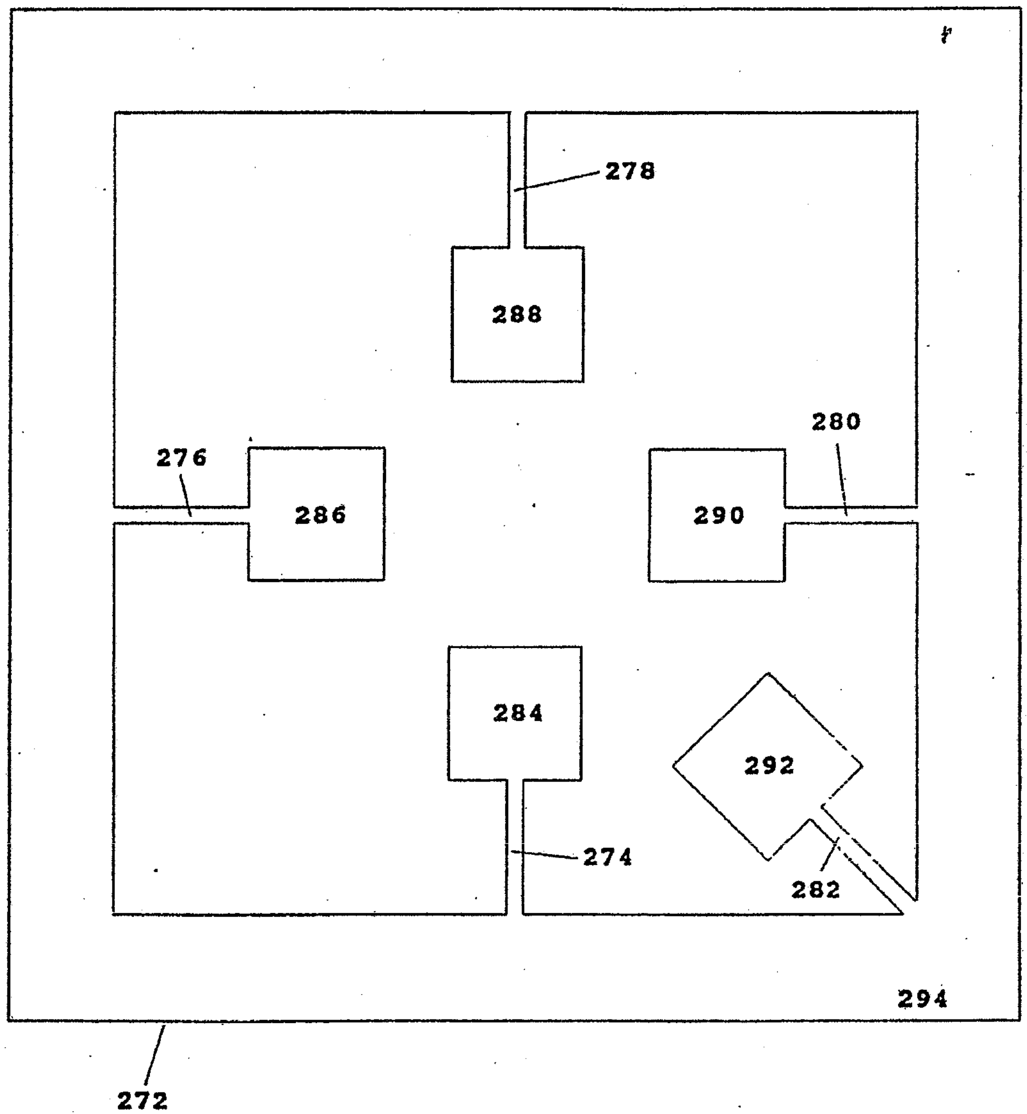
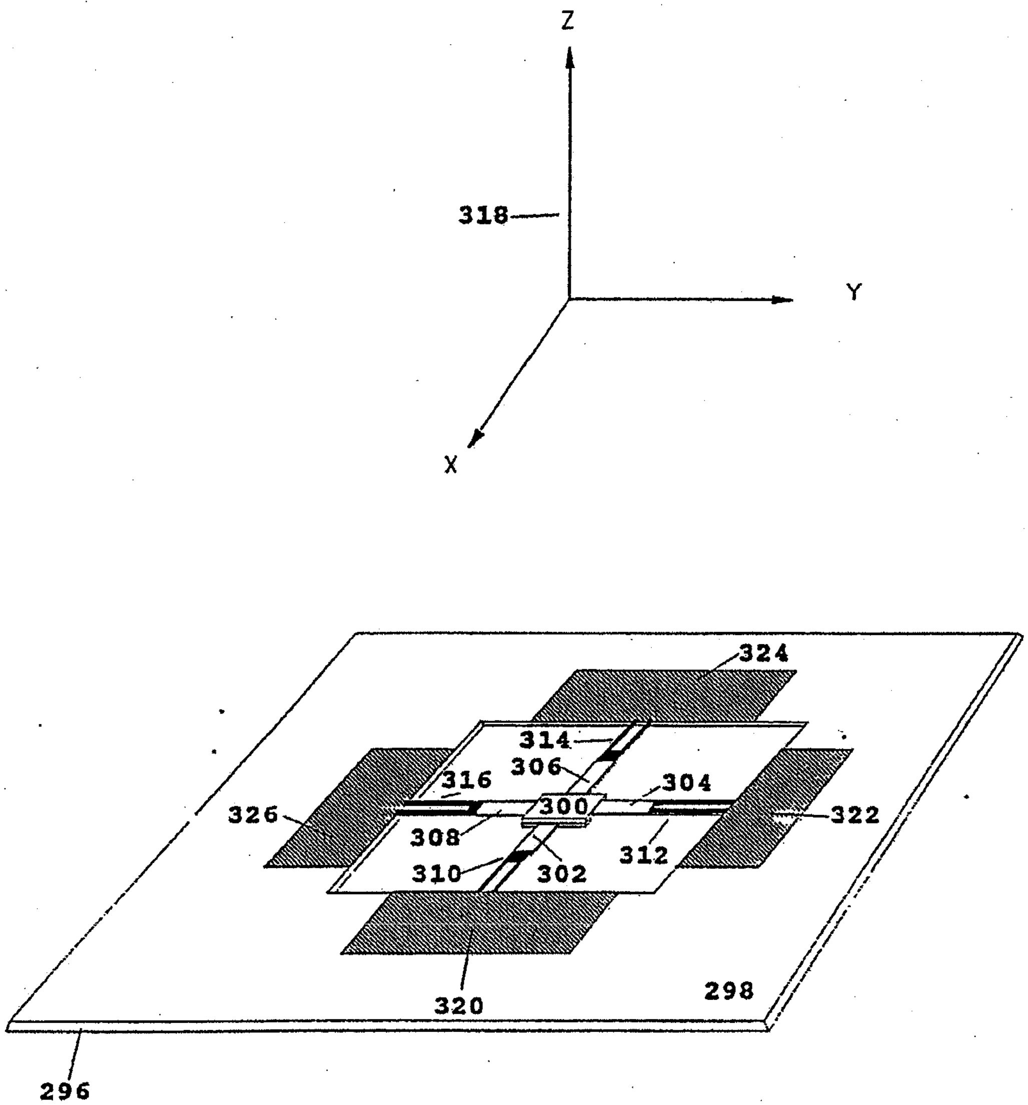


FIG. 23


Z
318
Y
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314
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316
300
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308
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310
302
320
298
296

FIG. 24

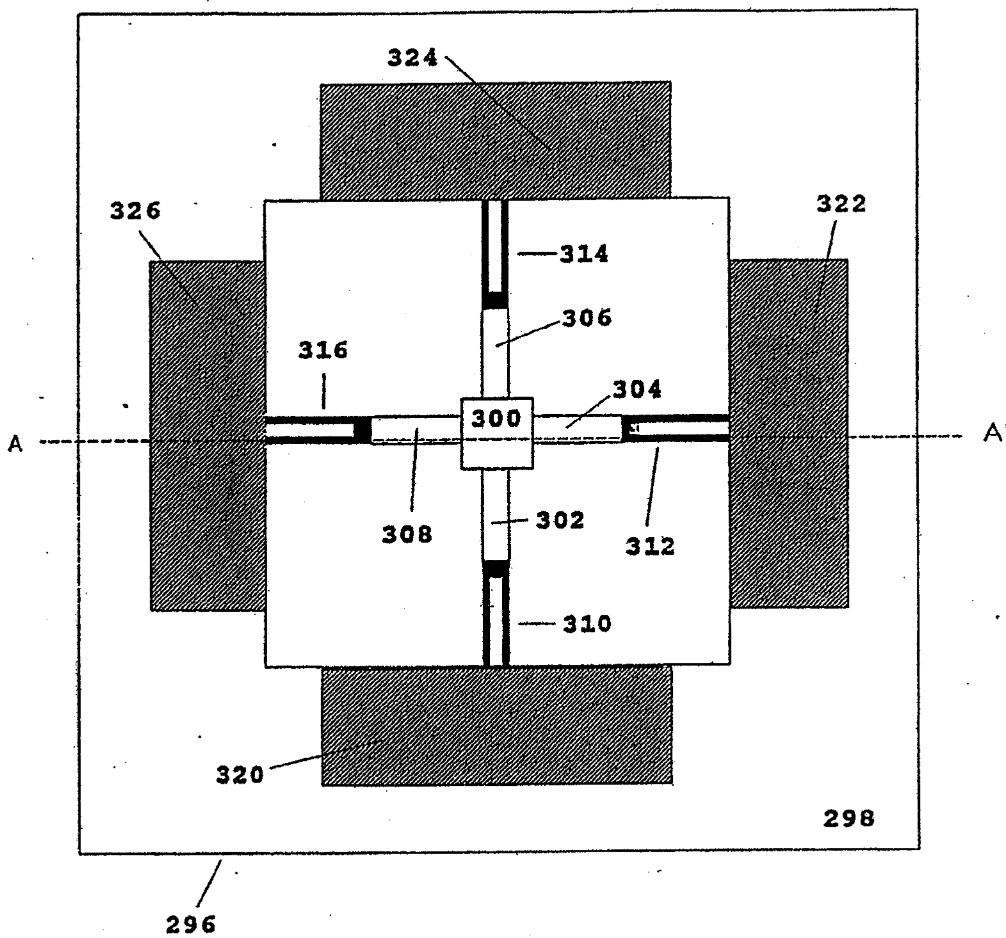

FIG. 25

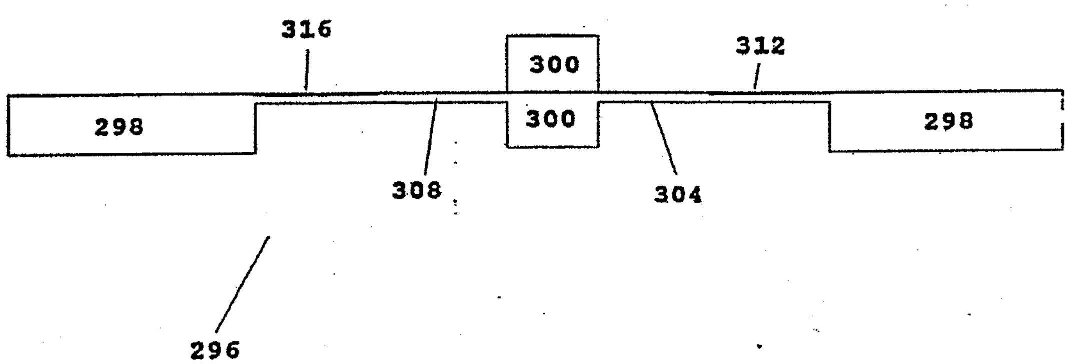

FIG. 26

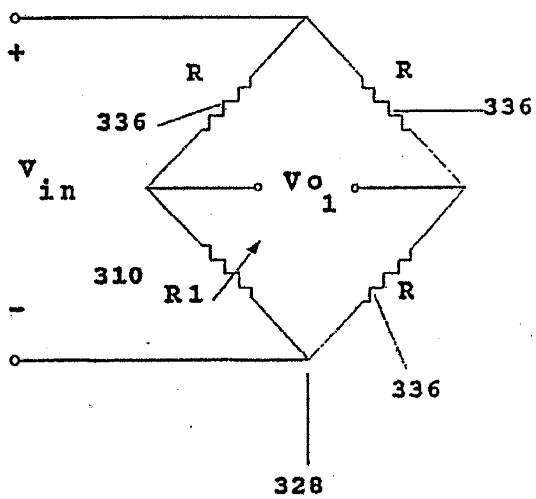

FIG. 27a

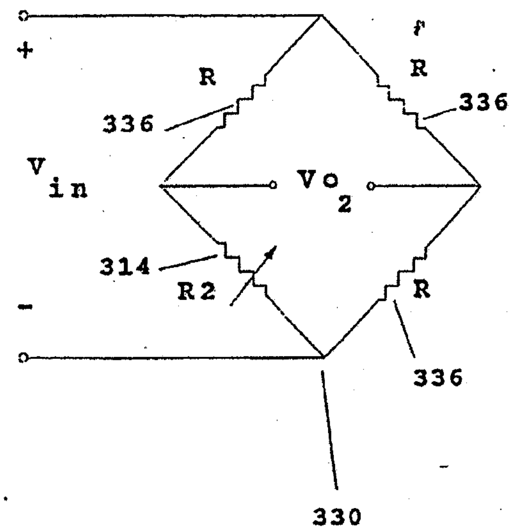

FIG. 27b

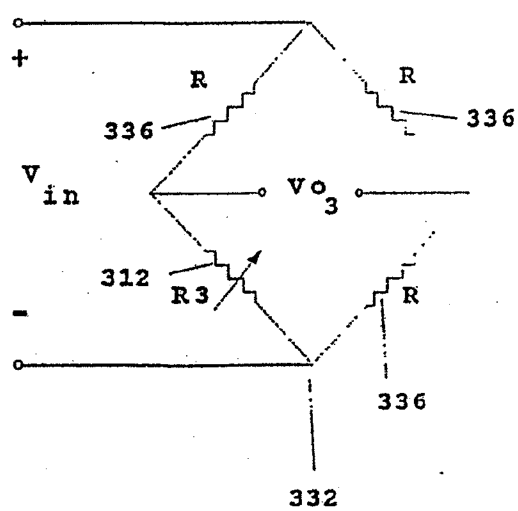

FIG. 27c

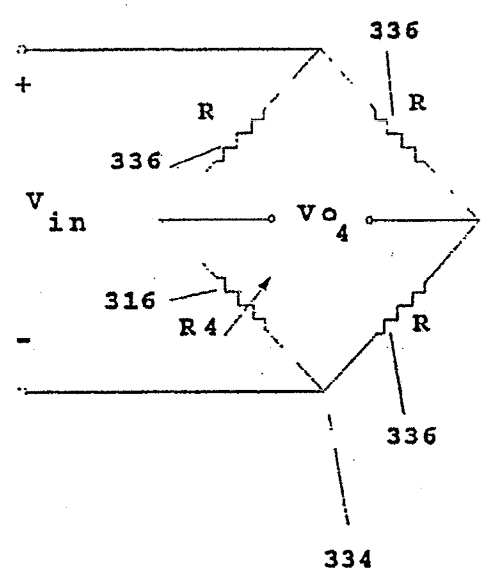

FIG. 27d

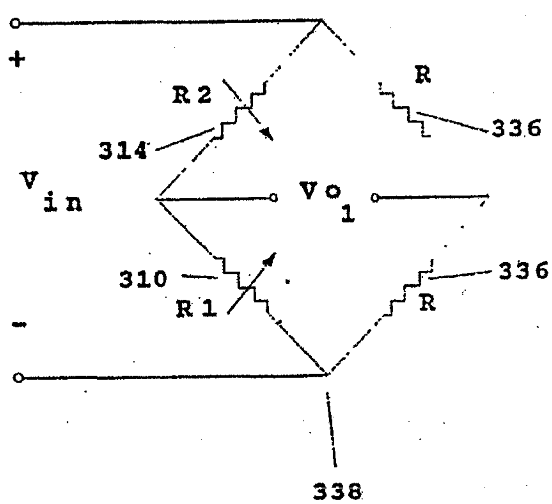

Fig. 28a

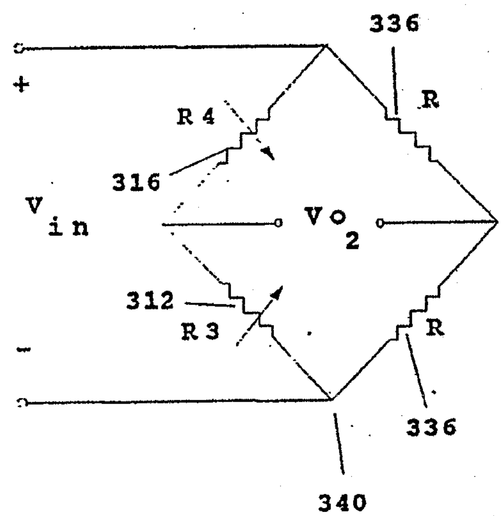

Fig. 28b

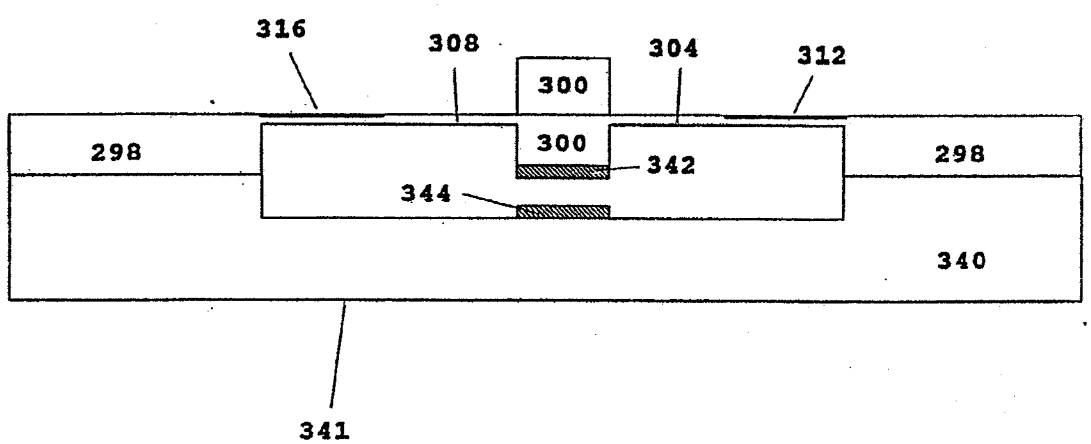

FIG. 29

SUBSTITUTE SHEET

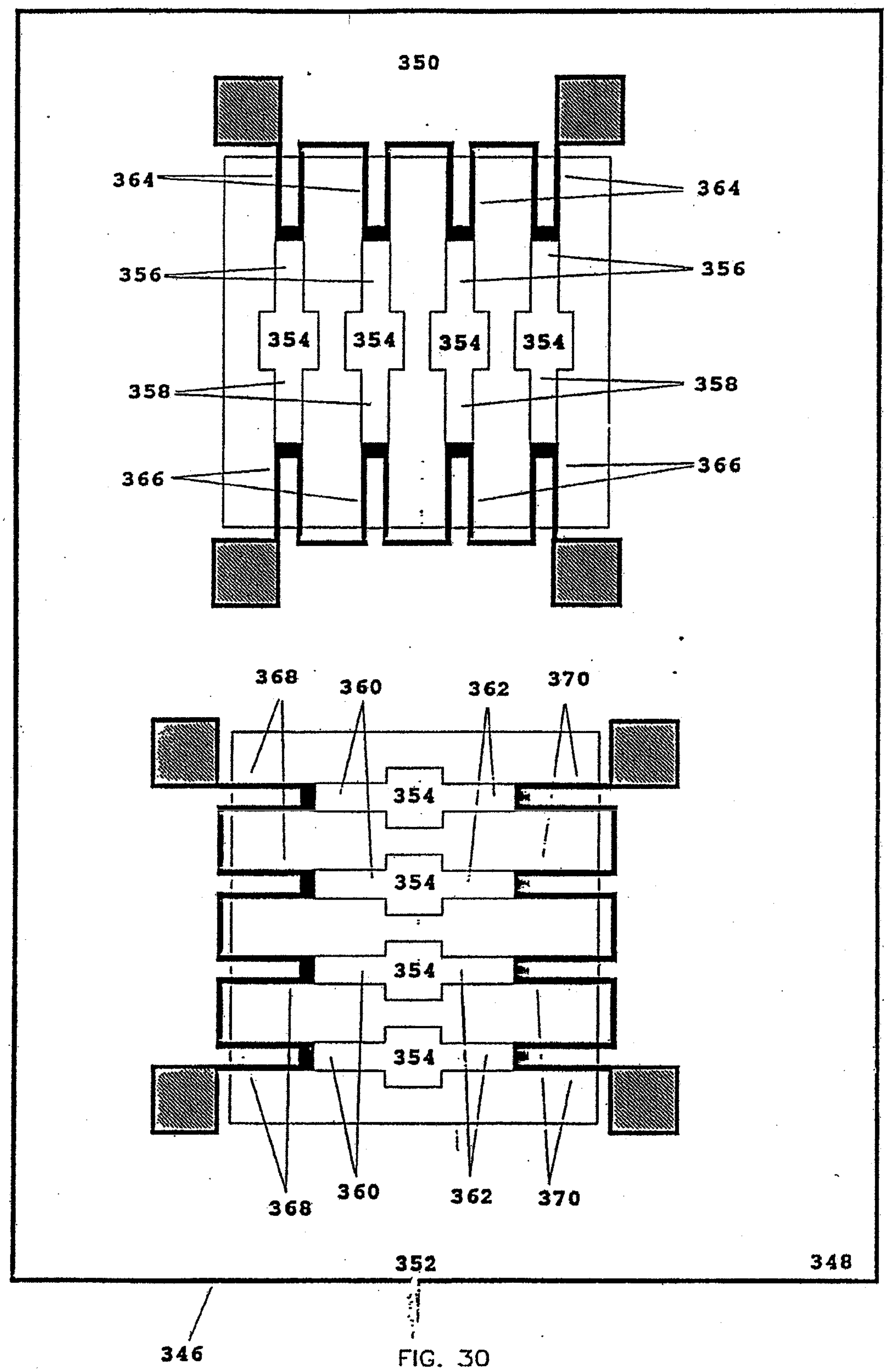
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FIG. 30

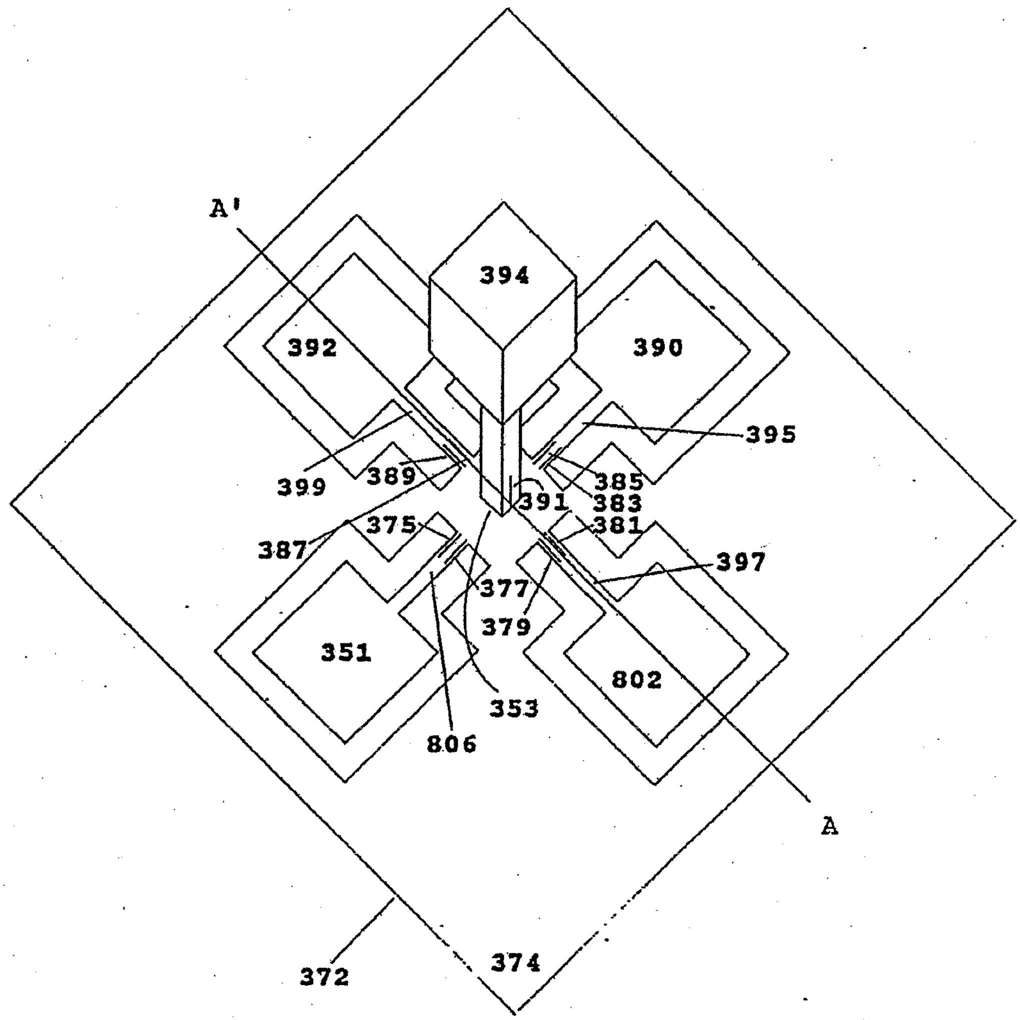
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FIG. 31

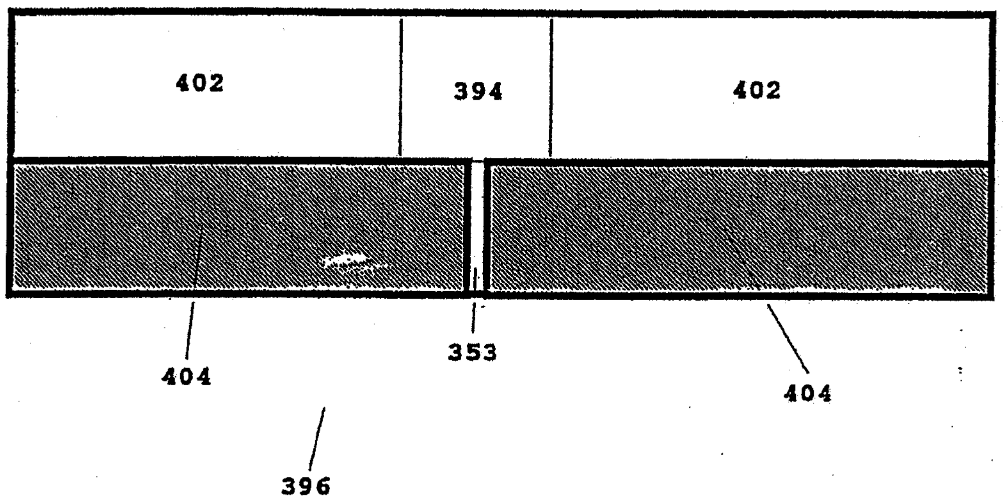


FIG. 32a

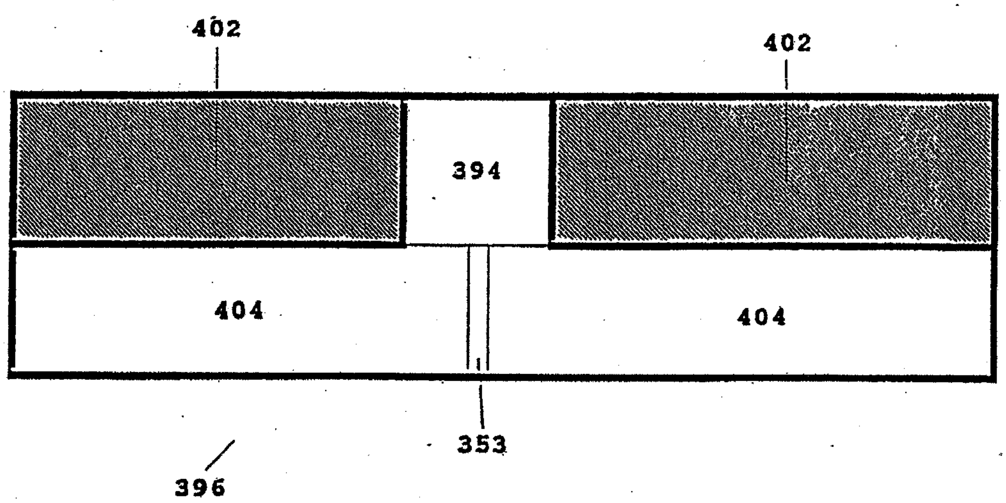


FIG. 32b

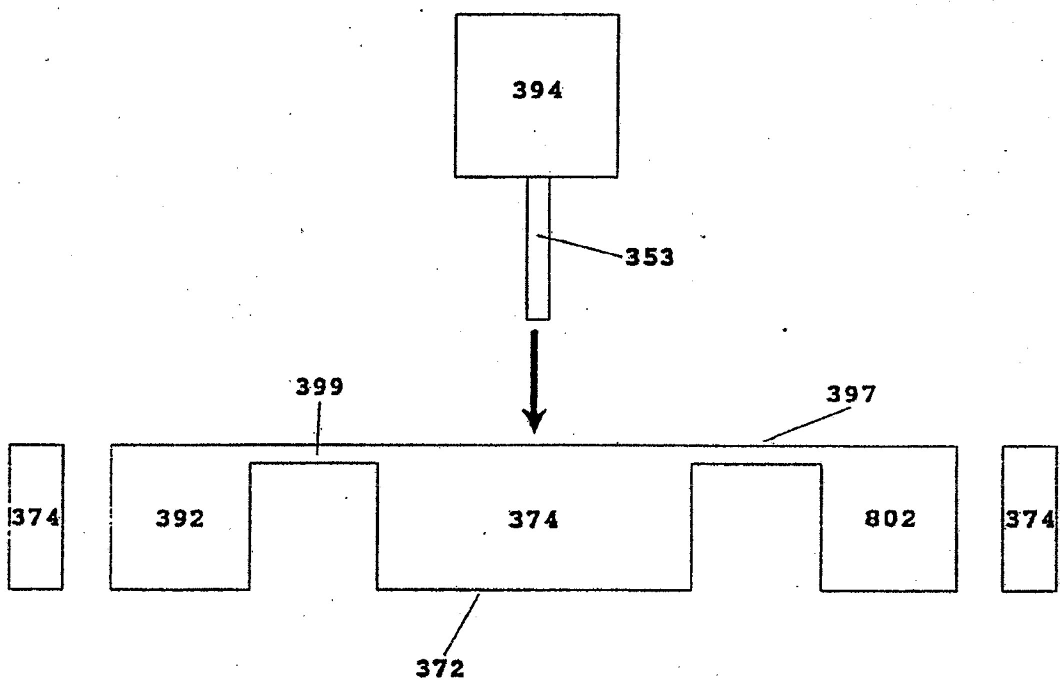


FIG. 33

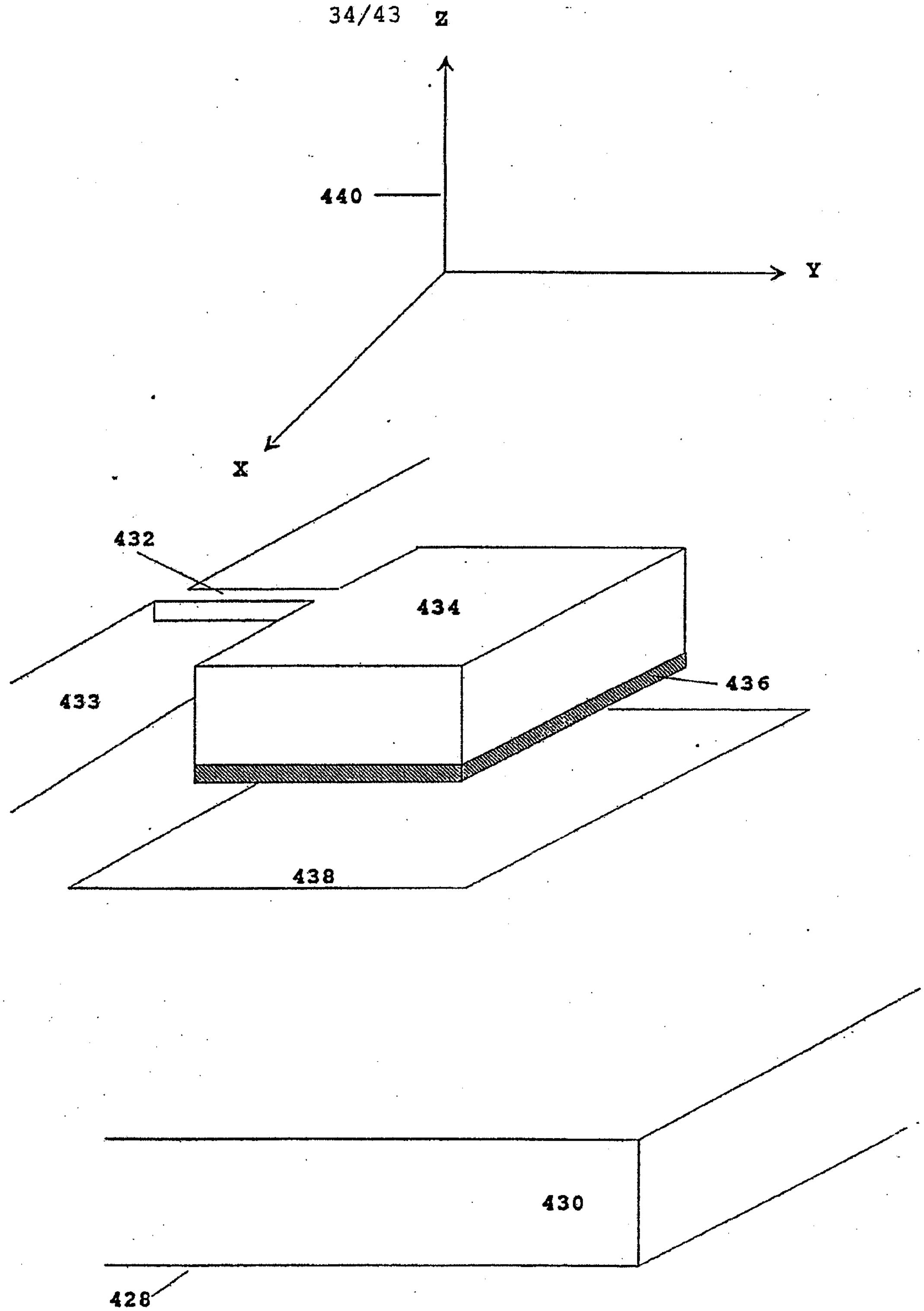


FIG. 34

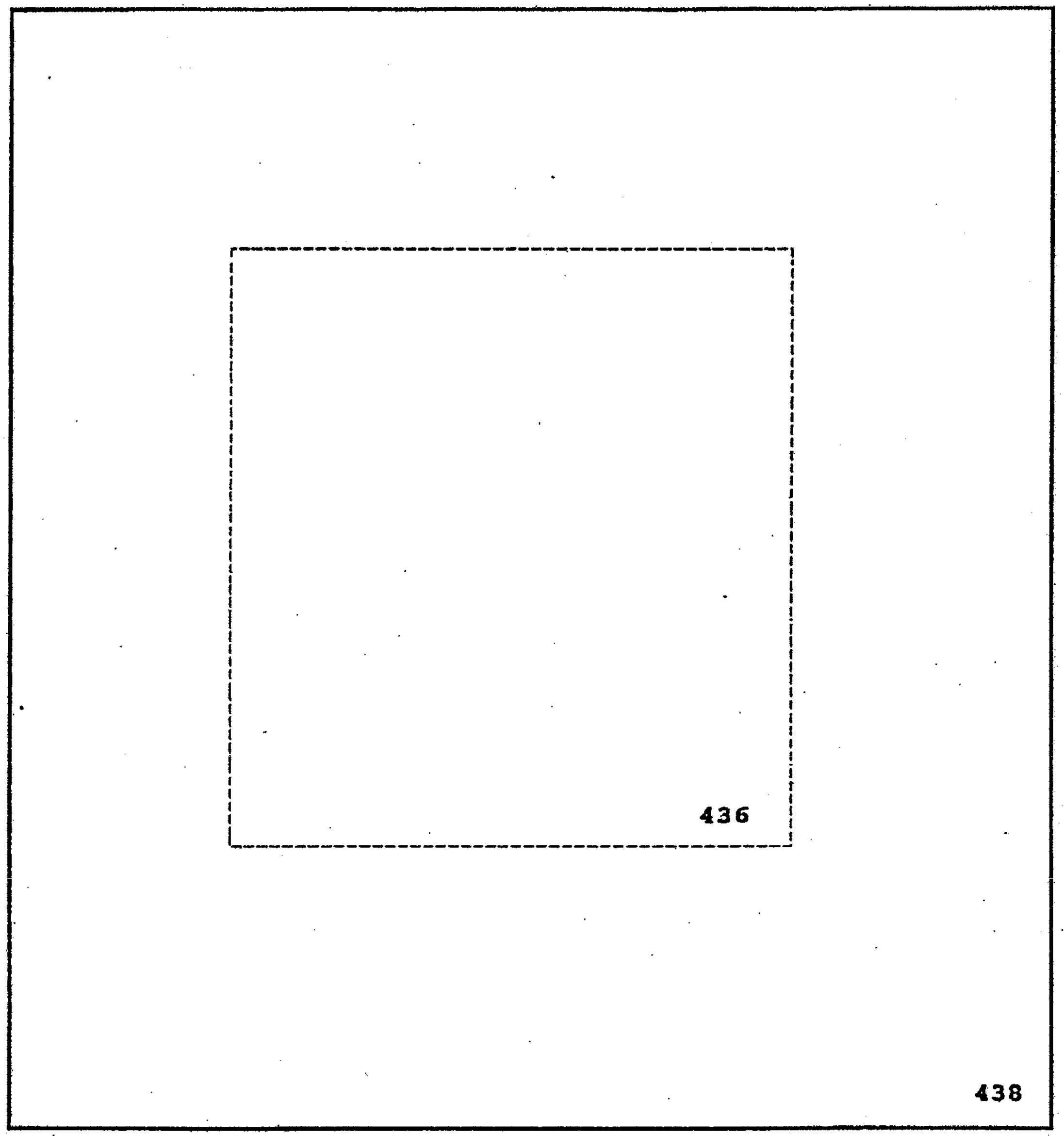


FIG. 35

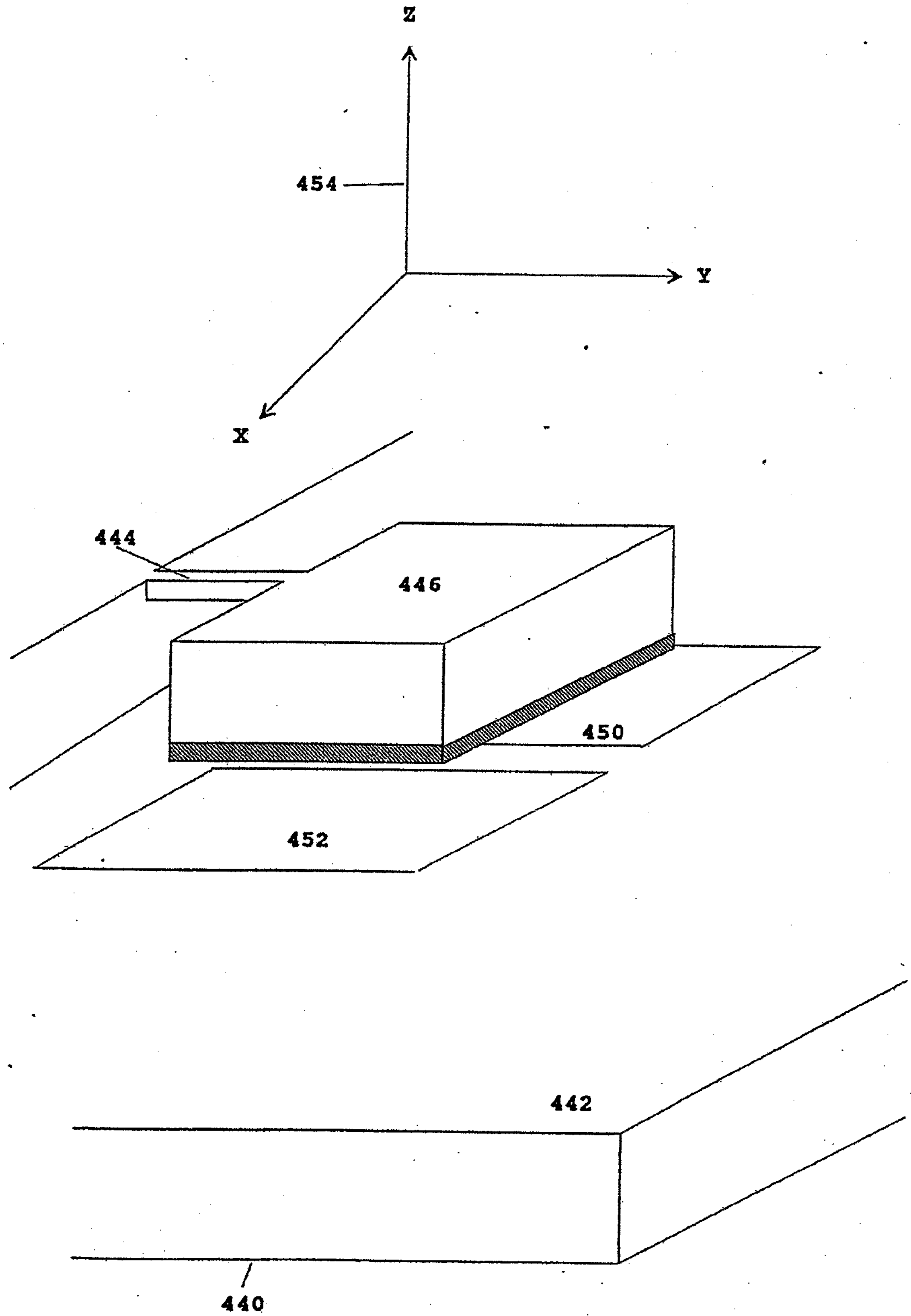


FIG. 36

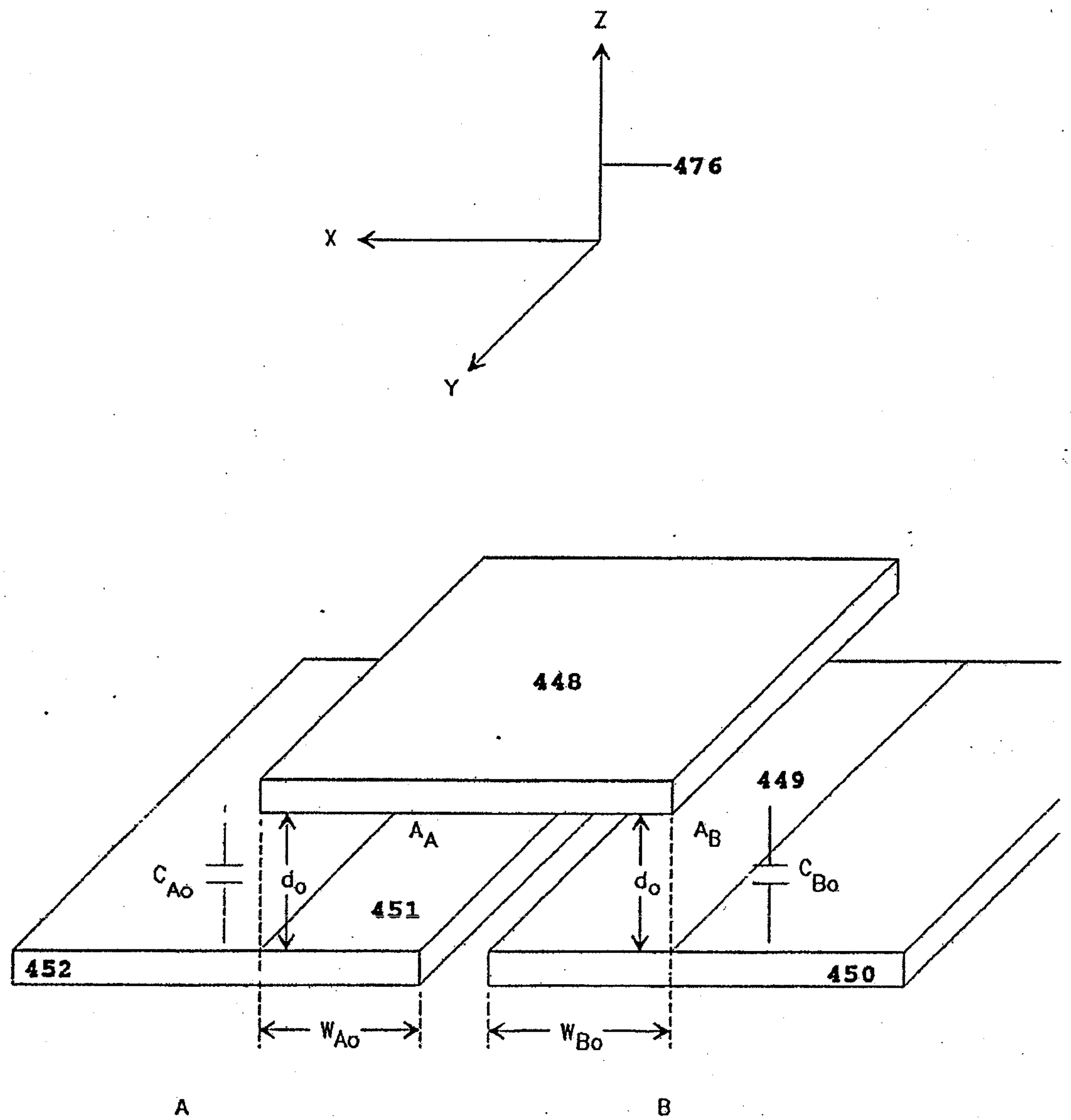


FIG. 37

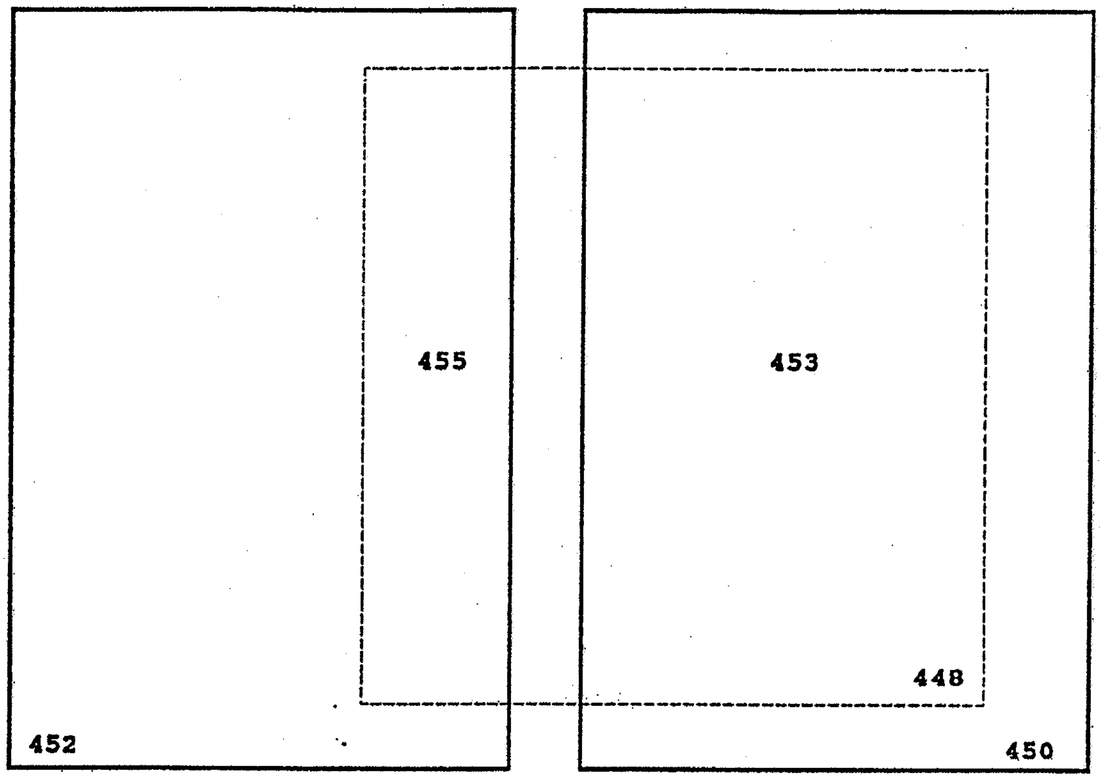
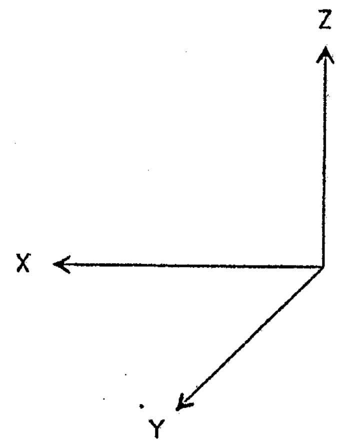


FIG. 38



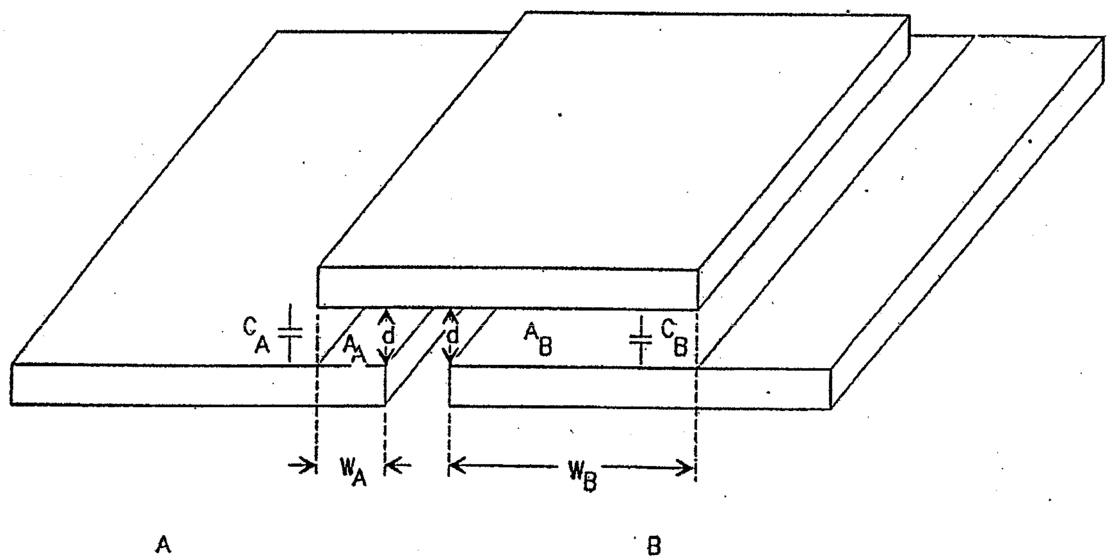


FIG. 39

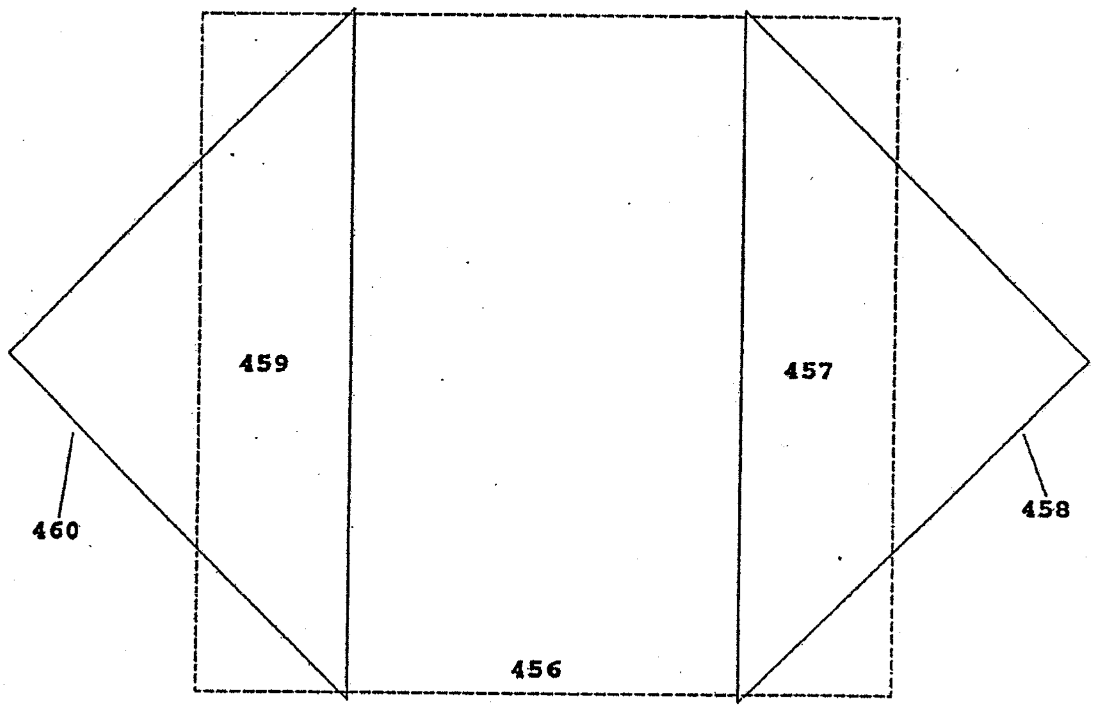


FIG. 40

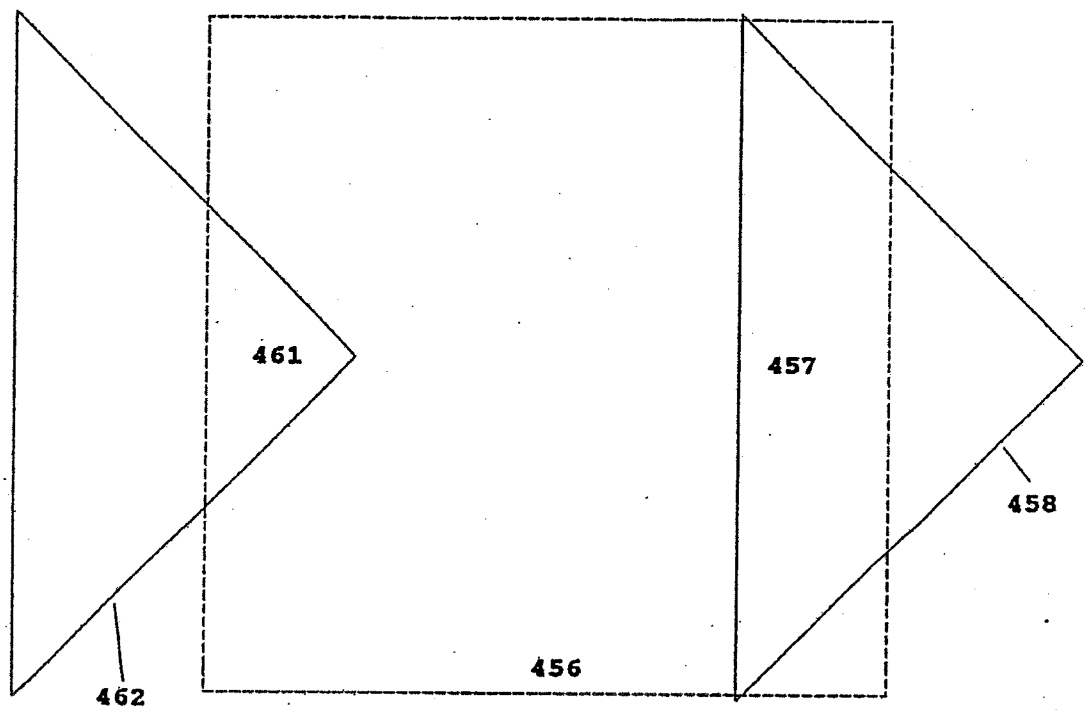


FIG. 41

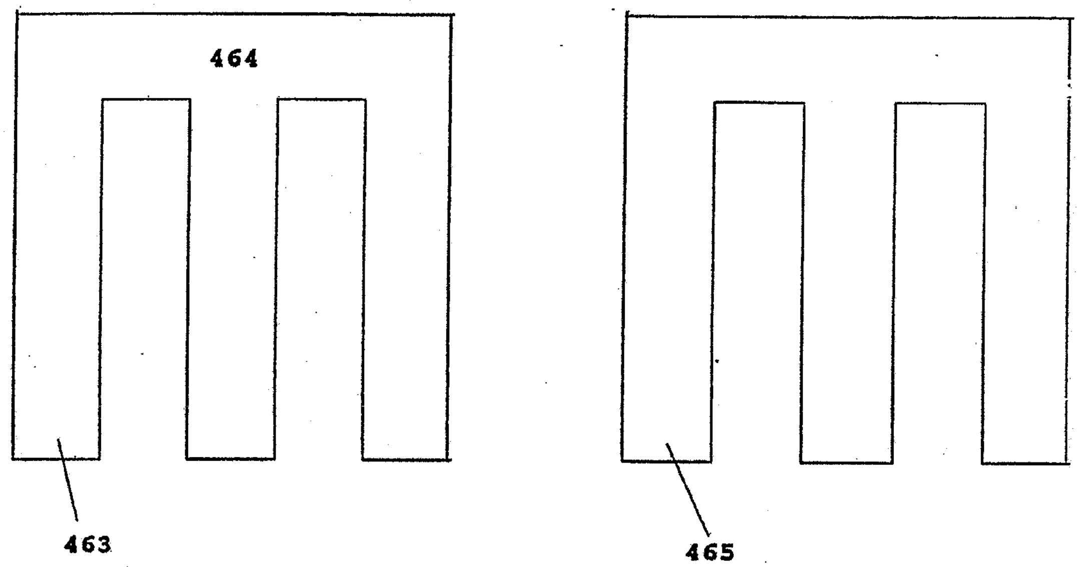


FIG. 42A

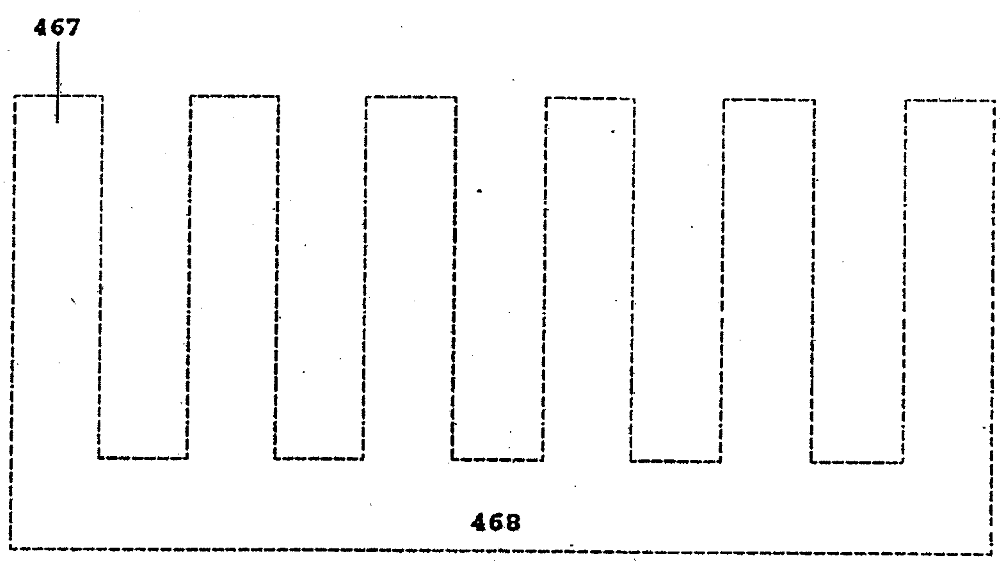


FIG. 42B

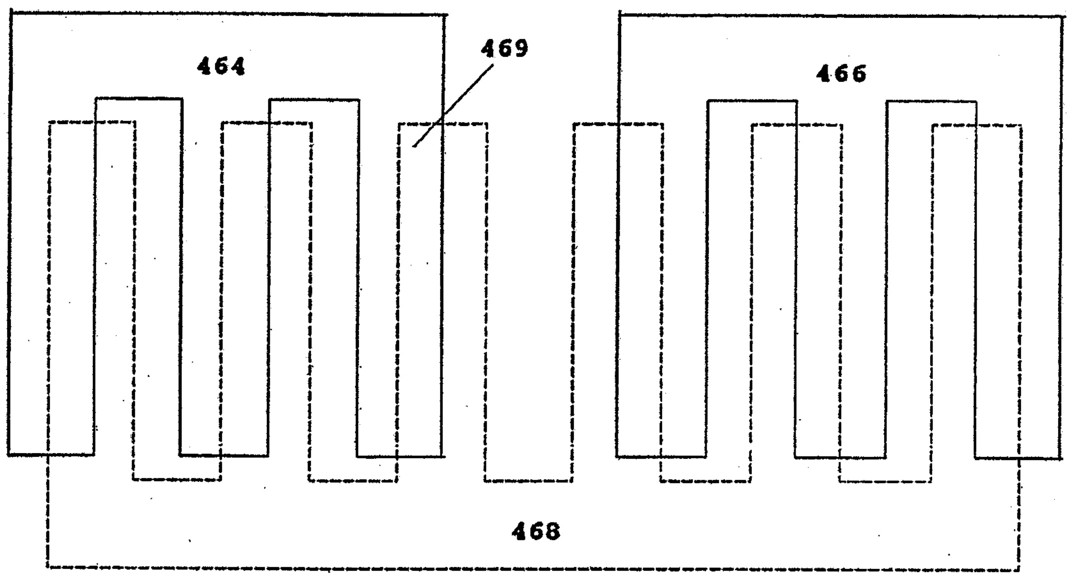


FIG. 43

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US 89/03075

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC
IPC(4): G01L - 5/16; - G01P - 15/08
U.S. Cl. 73/862.04, 517R

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S.	73/505, 510, 517R, 862.04, 862.05, 862.06, 862.64; 340/870.37; 361/278, 280

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	US, A, 3,304,787 (CHIKU et al) 21 February 1967, see column 8, line 71, to column 9, line 29.	131, 132, 145 146, 159-163
X Y	US, A, 3,693,425 (STARITA et al) 26 September 1972, see column 3, line 11, to column 5, line 32.	1,84,85 109/4-7 110/4-5
X Y	US, A, 4,303,919 (DIMEFF) 01 December 1981, see column 2, line 63, to column 4, line 15.	151,152,155,156 153, 157, 165
X Y	US, A, 4,342,227 (PETERSEN et al) 03 August 1982, see column 3, line 60, to column 4, line 68.	1-9,12,17,18, 159-163 10, 13-16
X Y	US, A, 4,552,028 (BURCKHARDT et al) 12 November 1985, see column 2, line 36, to column 3, line 50.	147, 159-163 148, 153, 157, 165

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
29 September 1989	30 OCT 1989
International Searching Authority	**Signature of Authorized Officer**
ISA/US	Charles A. Ruehl Charles A. Ruehl

International Application No. PCT/US 89/03075

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
X Y	US, A, 4,711,128 (BOURA) 08 December 1987, see column 2, line 54, to column 5, line 9.	1-8,11,12,17, 18, 159-163, 126/2 9, 10, 13-16, (127-130)/2
X Y	JP, A, 63-118,667 (FUJITSU Ltd.) 23 May 1988, see English language abstract.	84, 85, 91, 96, 131-135, 140, 145,146,159-163 87-90, 92-95, 136-139,141-143
Y	Transactions on Electron Devices, VOL. ED-26, No. 12, December 1979, L.M. Roylance et al, "A Batch-Fabricated Silicon Accelerometer", see pages 1911 to 1917, especially page1915.	15, 16, 94, 95, 143,154,158,165